PerFORMance:
Integrating Structural Feedback into Design Processes for Complex Surface-Active Form

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Per**FORM**ance:
Integrating Structural Feedback into Design Processes for Complex Surface-Active Form

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“What you have got to realize is that every point of curvature is a structural possibility.

What are required are new strategies for recognizing structural possibilities.”

Cecil Balmond

The spirit of this paper is dedicated to Laith Kai. Explore and Play!

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TABLE OF CONTENTS

PART TWO | FINITE ELEMENT ANALYSIS

PART THREE | DESIGN EXPERIMENTATIONS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

This thesis researches the potential for using Finite Element Analysis/Modeling as an analytical design tool for Architects and Engineers in designing both static and dynamic surface-active constructions. Preliminary geometric configurations will be input into FEA solvers and analyzed in order to test feasibility and as a means for producing structural surface geometries. The paper tries to develop a working methodology for designers to use this technology as analytical feedback in an iterative design process.

CHAPTER 1 | INTRODUCTION

Architecture is two-fold. There are **Atomic-Architectures** made up of bits of matter and there are **Meta-Architectures** made up of bits of thought. Atomic-Architectures are the metric material conditions and behaviors of the built environment. Meta-Architectures are the abstract generative and communicative devices [i.e. *languages* of thought and design] through which architecture lives outside of the material world. Often times these two realms are in tension with each other. Designs from the Meta world eventually [if actualized, see Rahim below] must make the transition into the material world. This transition is often forced and unpleasant if the two worlds were not communicating throughout the design process. This often results in built works where the Meta and the material are divorced from each other in the final production. If we are to take steps towards the development of a more holistic architectural design process we must recognize that architecture must be about the material and the immaterial, and the open dialog between these two worlds. How can the material world of Atomic-Architectures influence the conceptual world of Meta-Architectures and vice-versa? How can design be ***both/and*** rather than ***either/or***?

Ali Rahim has defined the dialog between the Meta and the Atomic as a process of ***Actualization***. Actualization is a process of transmutation from a space of infinite possibilities embodied within the virtual to a space of metric physicality. Rahim describes this concept in the introduction to his book *Catalytic Formations*.

> I explore the concept of the virtual as a space of potentialities, distinct from the tangible, measurable world of *actual* space. Temporal techniques such as digital generative and transformational methods contain an element of the virtual: this is what allows them to give rise

> to unexpected results. The translation of a design from virtual to actual space is called actualization, and always entails discovery because the actual, by nature, is never the same as the virtual. Working with virtuality produces what I call formations - projects that incorporate feedback from their users and environments, continuing to change even after they are built. Formations do not conform to traditional concepts of architectural type and program, as the effects and modes of occupation of such formations shift constantly.[1]

The ultimate goal of this research is to develop a method, from the designer's point of view, for using the embodied specialized knowledge of **Finite Element Analysis** [FEA] software to study the behavior of **materials, geometries, and configurations** in order to create an **iterative design feedback loop** that uses **structural performance** as a primary evaluation criteria and point of departure for generating and refining complex formo-techtonic configurations while ensuring **constructability, improved structural performance, and syntactic consistency**. Syntactic consistency meaning that there would not be a loss in translation from concept to construct. Instead of the 2-dimensional [planar] manual technology which drove modernist analysis towards the structural hyper-rationality of the trabeated system, as in Corb's Domino House, this new process should **compile and synthesize computational speed, mathematic principles, mechanical knowledge, and material logics** within a digital 3-dimensional [spatial] analytical environment in order to realize a new paradigm of constructible spatialized sensuality. The research will focus on the development of interoperability techniques and protocols between advanced parametric CAD systems and advanced

[1] Rahim, Ali. Catalytic Formations: Architecture and Digital Design. New York: Taylor & Francis, 2006, p. 5

structural analysis systems towards the creation of a fluid design + analysis process of creating and engineering complex forms and dynamic systems. Rapid prototyping will be integrated as a secondary feedback and verification loop, and as a precursor to the production of full scale construction machine readable files. In other words, the research focuses on the development of intricately designed, geometrically complex, and materially sophisticated **structural skins** that can be produced through advanced CAD/CAM techniques.

Webster's defines the word ***Opportunity*** as, 'A chance for progress or advancement'. This process tries to create **design opportunities** that can be discovered, developed, and materialized by peeking into the invisible world of physics and geometry from the initial phases of design. These opportunities can manifest themselves in one of two ways. Either as the static results of a dynamic and iterative design process, or as potentially dynamic structures that analogously align themselves with living organisms. This paper will focus on the first type as a matter of sequence and will speculate on the future potential of the second type as a matter of progression.

PART ONE | THE ARGUMENT - FORM, SPACE, AND STRUCTURE

CHAPTER 2 | THE PROBLEM AND ITS POTENTIAL

Somewhere between Peter Eisenman's appropriation of Deleuze's theory of *The Fold*, computational speed and cheapness, Graphical User Interfaces [GUI's], NURBS, CNC machines and high gloss printing the architecture of the past fifteen years has been about complexity. This complexity has manifest itself formally, spatially, geometrically, conceptually, organizationally, topologically, structurally, and visually; and in turn it has propelled a departure from linear notions of Euclidean space. Although highly controversial, these high gloss paper constructs have captured the imagination of the architectural academy and indulged the vulgar pleasures of the populous. An analysis of why these complex forms are aesthetically pleasurable and the infantile nature of the forms need be asked again elsewhere. For the moment we will ask ourselves the following two questions. First, why have so few of these complex buildings been built [even in times of such economic prosperity] and second, why have the primary structural systems of most of those built projects been divorced from the conceptual questions which are driving the projects? That is, why are the structural systems of most of these complex projects, or blob-itectures, normalized within industry and engineering standards? Have we really entered a new paradigm of design or are these designs just 'curvy' versions of traditional design and construction practice?

When the steel frame and concrete frame became normalized within the construction industry at the turn of the century a method of mathematical analysis was developed to help the design team study the building based on the mechanical principles of column and beam which are analogous to Euclidean notions of straight, discrete lines in space. This analytical model of verification fueled the design process, ultimately reinforcing the technocratic calls of modernism which still dominate our contemporary construction paradigm.

The cause for this type of analysis can be traced back to the inability of mathematicians and engineers to pragmatically calculate nonlinearities before digital computing. This inability led the sciences to develop techniques of approximation for nonlinearity through linear equations. Mathematician Ian Stewart explains:

> Classical mathematics concentrated on linear equations for a sound pragmatic reason: it could not solve anything else…So docile are linear equations that classical mathematicians were willing to compromise their physics to get them. So the classical theory deals with shallow waves, low-amplitude vibrations, small temperature gradients [that is, it linearizes nonlinearities]. So ingrained became the linear habit that by the 1940's and 1950's many scientists and engineers knew little else… Linearity is a trap. The behavior of linear equations… is far from typical. But if you decide that only linear equations are worth thinking about, self-censorship sets in. Your textbooks fill with triumphs of linear analysis, its failures buried so deep that the graves go unmarked and the existence of the graves goes unremarked. As the eighteenth century believed in a clockwork world, so did the mid-twentieth in a linear one.[2]

Within this scientific paradigm architectural theories of the grid where produced as conceptual design devices and perhaps as post-justification for our inability to conceptualize and calculate nonlinearities. Eisenman's Wexner center is perhaps a good example of an architectural project which is situated at a moment in time [late 1980's] when the power of the computer is about to unleash potentials that will turn

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[2] DeLanda, Manuel. "Material Complexity," Digital Tectonics. Chichester, West Sussex, U.K.; Hoboken, NJ : Wiley-Academy, 2004, p. 17.

theoretical fantasy into calculable, constructible realities. The Wexner center is organized as a spatialized Euclidean grid that is broken and disrupted by many anomalies. Is Eisenman indirectly hinting at things to come? This project directly precedes Eisenman's Rebstock Plan in Frankfurt where the theory of the fold is implicated on the urban scale. The body of Eisenman's work during the late 80's and early 90's is critical for the theoretical ruptures that occur during the early 90's.

These ruptures in the discipline were defined by the shift of thought from notions of space and dimensionality as being defined by discrete Euclidean coordinates to conceptions of form being described by continuums of curvature and surface, i.e. *The Fold*.[3] These mathematical and philosophical theories of magnitudes were always available for architectural appropriation but were highly disregarded within the discipline until the 1990's. This was the moment when the promise of computation became evident to the design avant-garde as architects looked to techniques of animation coming from Hollywood.

Today we find ourselves having appropriated what Greg Lynn calls 'a 300-year-old mathematical and spatial invention'[4] in reference to calculus and having mastered the representational production of the blobs, folds, cells, webs, cracks, crystals, fractures, plumes, drips, nests, sponges, shells, et cetera. Now architects are left asking themselves the age old question which architects must ultimately ask: 'How do we build

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[3] Deleuze, Gilles. The Fold: Leibniz and The Baroque. Minneapolis: University of Minnesota Press, 1993.

[4] Lynn, Greg, and Carpo, Mario. Folding in Architecture. Chichester, West Sussex ; Hoboken, NJ: Wiley-Academy, 2004, p. 9.

it'? Thus far we have usually seen a material-spatial schism at this point in the design process into a fairly normalized stick frame structural system clad with a complex skin. This schism is caused in large part by our inability to integrate the structural analysis of complex forms into a fluid design process based on a design + analysis feedback loop pushing towards structural feasibility and optimal system performance that is based on geometry and materiality. This is the primary problem in realizing these complex forms in the physical world while maintaining conceptual consistency.

Cecil Balmond describes the nature of the disciplinary problem in the introduction to his provocative monograph *Informal*.

> There is a lot more to structure than strict post and beam. Slabs may fold and act as lines of vertical strength, beams may bifurcate and change shape, columns can serve as beams, the ingredients are all there to evolve form in fascinating ways. The challenge is to make structure the new discipline in a re-examination of space.
>
> Now the computer opens a door and gives unparalleled freedom to explore – the result is a bewildering and mind bending free-for-all where anything goes. But cool new shapes and blobs are nothing more than mere façade if they are propped up by standard post and beam constructions. To create an integrity in the establishing of a free shape a new method is needed for configuration with flexible start points. Instead of line – surface; instead of equi-support – scatter; instead of fixed centre – a moving locus; and instead of points – zones.[5]

While the building industry has not progressed much in the last century regarding its concept of structural geometry the automotive and aerospace industries are leading

[5] Balmond, Cecil, and Smith, Jannuzzi. Informal. Munich; New York: Prestel, 2002, p. 14.

the way in terms of complex hybridized design and construction methods. Monocoque construction is a good example of these types of hybridized components, which are often used in the fabrication of airplanes. In fact, much of the mathematical basis for contemporary B-Rep CAD packages, the ones with which architects are so in love, is derived directly from the work of French mathematician and automotive engineer, Pierre Bezier.[6] Using FEA software like Altair Engineering's Optistruct and LS-Dyna the automotive industry is able to design and analyze complex geometry and material configurations on a much shorter time cycle and in a highly iterative fashion. These other industries should be studied and architects should try to learn from their innovations and incorporate their procedures. Some softwares that have been appropriated by architects like Dassault Systemes Catia do incorporate FEA directly into the package for analysis. However, these capabilities are still used primarily in the evaluation process to verify the design from an engineering perspective. Jeff Turko advocates the idea of architects using automotive crash testing software in his essay *Virtually Crash Testing The Box*.[7] These interdisciplinary approaches are, and will continue to be, critical to the future of the design profession.

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[6] While Bezier's work was monumental for the development of representing complex surfaces, today most modelers use NURBS surfaces for improved control and detail.

[7] Turko, Jeff. "Virtually Crash Testing the Box," Contemporary Techniques in Architecture. London; New York: Wiley-Academy, 2002, p. 93-94.

The Role of the Architect and the Changing Structure of Practice

It has always been the role of the architect to synthesize the tools and research of the pure and applied sciences. We are at a moment in the history of the discipline when we must reestablish our role as the Conductor of the design process. Jean Nouvel equates this role to the role of the film director. We only have to look at the history of George Lucas and ILM to see the impact of innovation and technology on industry and medium. This will mean ever more research into the design of design, i.e. design process. Only through innovation will either the profession or the discipline survive and continue to be a significant force for cultural reflection and change. Ali Rahim argues, "In order to produce design innovation, architects cannot simply be passive recipients of technological change but, instead, must participate actively in this feedback loop between technology and culture."[8]

How can the designer engage/interact with state-of-the-art technology in order to move beyond the current design process and into a new realm of simulated interactive design? The design process has always been about two-way flows between designer and tool. Brunelleschi developed the perspective as an interactive design tool, i.e. as a new technology to be deployed by the architects of the Renaissance. Today many people including figures such as Greg Lynn, Ali Rahim, Mike Weinstock, and many others are advocates of using computational power as the next truly interactive design tool, very much in the vein of Brunelleschi's radical new technique called Perspective.

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[8] Rahim, Ali. Catalytic Formations: Architecture and Digital Design. New York: Taylor & Francis, 2006, p. 10.

There must be a dialog between the artifact and the author. We should first consider the reality of an existing interactive design process that occurs with conventional drawing methods. Do we draw just to communicate with others? I believe not. We draw in order to make a representational artifact with which we can commune. In other words, we already strive to work within a method of interactive feedback and are perhaps not even aware of it and do not take full advantage of this procedural paradigm. What does the drawing tell us? What is revealed through the act of drawing? Can we predict how a drawing might 'look' and what it might 'say'? Do we want to? We even give drawings human characteristics with expressions such as 'what does this drawing SAY to you'. Should design be positivistic [verificational] or constructivistic [experimental]? What does the experiment tell us? How do we progress? How do we transition into new paradigms based on experimental results? Architects have used physical models to iteratively test and modify their ideas since at least as far back as the Renaissance. The transition to virtual model testing and feedback seems a natural one.

'Process' is defined by Webster's as: 'A series of actions, changes, or functions bringing about a result'. If we are to accept the philosophy that design is a **process** we must now start to embrace computation as a sincere member of the design team's procedural structure that is 'a series of actions, changes, or functions' that bring us to a design conclusion. Neil Leach describes the relationship of the designer to the computer within this new context:

> The designer moreover, is using the computer not merely as a tool of representation but as a 'collaborative partner' within the design process itself, to such an extent that our whole notion of design needs to be reconfigured.[9]

What is Computation?

By now we have indirectly established that we are discussing something called computation. Therefore we must ask an important question. What do we mean by computation? Terms like computation, digital, algorithm, and many more are thrown around loosely these days. However, many people are still unclear about how the computer can and does relate to contemporary design practice. Today it is clear to see how computational structures and power are used in the production and organization of design documents and building components. This is of course a very important and continually developing area of computation, with a particular emphasis on centralized 3D Building Information Models. It is, however, the glossy images from the past decade that have subconsciously defined the computer as a predominantly representational tool. In fact, what we normally call representation is only the 'output' at the end of a much more involved process of operating on **other types of representation** [non-graphic text based]. In general, computation is the automated execution of a set of rule-based tasks. Charles Babbage was one of the first figures to illustrate the concept of programmable computers with his *Difference Machines*[10] and Alan Turing first described the concept of

[9] Leach, Neil, Turnbull, David and Williams, Chris. Digital Tectonics. Chichester, West Sussex, U.K.; Hoboken, NJ : Wiley-Academy, 2004, p. 8.

[10] Charles Babbage, Wikipedia, Viewed 06 July 2006, <http://en.wikipedia.org/wiki/Babbage>

what could be computed with the introduction of his *Universal Computing Machine* in his paramount essay *On Computable Numbers, with an Application to the Entscheidungsproblem,* in 1936. Jack Copeland describes the conceptual basis of Turing's machine:

> The universal computing machine has a single, fixed table of instructions (which we may imagine to have been set into the machine, once and for all, by way of the switchboard-like arrangement mentioned earlier). Operating in accordance with this table of instructions, the universal machine is able to carry out *any* task for which an instruction table can be written. The trick is to put an instruction table - programme - for carrying out the desired task onto the tape of the universal machine.[11]

If then, computation is about rules and tasks we must consider the question of what are the tasks to be done and which rules do we use to execute those tasks. This is the true power of computation. Since software can be written by experts to perform expert tasks in an automated and accessible fashion, the designer can appropriate these computational task lists [i.e. software] to his own ends. In other words, diverse specialized knowledge, or rules, can be compiled, organized, and made accessible to the uninitiated for use in performing tasks at lightning speeds. This embodies the idea of collective thought, a tenet of intellectualism, and is in fact clearly articulated in the etymology of the word *computer* which comes from the Latin compound *con*, meaning

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[11] Copeland, Jack. The Essential Turing. Oxford: Oxford University Press, 2004, p. 15.

‘together’ and *putare*, meaning ‘reckoning’ or ‘resolving’. In other words, to compute means to resolve together through collective knowledge or interdisciplinary interaction.

Critical to this argument is the notion of ***accessibility***. The ability of designers to access various knowledge bases, through software, is the factor that makes computation so revolutionary in the realm of interdisciplinary practice. Stylianos Dritsas explains the relationship of access and interdisciplinary thinking through software in his essay *Design Operators*:

> Computation became a *universal language* that allows people from different disciplines to communicate using the same means. Once the initial obstacles are overcome, it seems that the problems of accessibility are not only resolved but rather reversed. For example, it is easier to approach complex mathematics, engineering principles, physics and other scientific areas with only a basic understanding of computation. It is also beneficial for artistic endeavors since all media are accessible by the same interfaces.[12]

While this paper advocates that designers can and should appropriate specialized knowledge for design conceptualization it must be stated that this is not a license to *do* anything without consultation and collaboration with the appropriate expert. Personal evaluations of appropriateness must also be considered. The notion of *appropriation* is meant to promote cross-disciplinary interaction and conceptual thinking. Architects armed with structural analysis packages are not meant to replace professional engineers just as webMD.com is not meant to replace medical doctors. But webMD.com

[12] Dritsas, Stylianos. Design Operators. MIT Thesis, 2004.

can educated the general public regarding physiological behavior and could promote better living habits just as structural feedback can help architects conceptualize more holistic buildings.

Now that we understand the generic nature of digital computation we can see how any number of specific design processes can be developed and implemented as a set of rules that perform a task. Today, generative algorithms derived from many diverse disciplines are being used in speculative computational design.

Engineering as Medium

In recent years we have seen many dualities between architecture and otherness. Biology, aleatoric art and music, nanotechnologies, etc have all been studied and used as analogies for architectural design. While I fully embrace the idea that we should look outside of the acknowledged profession for design logic and inspiration we should also consider the state of our immediate design medium as a rich field for exploration and discovery. This medium is one of material, geometry, and configuration. By taking engineering knowledge and writing logical rules to perform tasks within the computer, Finite Element Modeling provides a platform for architects to experiment with the bread of butter of the built environment, form and matter.

Today architectural design is dyadic; headed by architect and engineer. The relationship of the designer to the engineer is often times a linear, bi-polar relationship with designer on one end making formo-spatial decisions and the engineer on the other making material and configurational decisions. The two disciplines are seen as distinct and somewhat incompatible and sometimes disconnected. It is this distinction which must give way in order for a new type of design process to emerge and for a new holistic architecture to occur. Architects must embrace materialogy and physics and engineers must open themselves to design innovations and speculation. In ancient times this harsh distinction did not exist. According to Cecil Balmond, 'in the Greek word 'techne' the unity of engineer-architect describes a sharing of design values, the diagram and calculation, the concept and proportion being viewed as cycles of noetic invention".[13] Balmond goes on to describe the future potential for the appropriation of engineering knowledge into the design process through the use of digital technology.

> There is now an almost unrestricted access to information, and this contributes to the breakdown of barriers between disciplines, a dismantling of the 'professional' protection of separate and specialized practices and the emergence of integrated, multidisciplined 'designer' practices.[14]

The root of this disciplinary disconnect and compartmentalization can be found deep within the pedagogical structures of schools of architecture and engineering where students are taught to think like one or the other right from the start. Mark Burry and Manuel DeLanda comment on this crisis in a round table discussion published in Neal Leach's *Digital Tectonics*:

> … Burry comments on the emphasis on being 'hip and creative' over possessing technical ability in the admissions policies to certain schools of architecture. This

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[13] Balmond, Cecil, and Smith, Jannuzzi. Informal. Munich; New York: Prestel, 2002, p. 13.

[14] Balmond, Cecil. "The Digital and The Material," Contemporary Techniques in Architecture. London; New York: Wiley-Academy, 2002, p. 48.

> is a symptom of a culture in which 'stress' and 'strain' have become dirty words for architects, just as 'aesthetics' has become a dirty word for engineers. What we need, notes DeLanda, is a means of enthusing architecture students with technical concerns and engineers with aesthetic ones…This would help to produce, perhaps, a hybrid discipline, an 'architecture-engineering' of the digital age…[15]

Is engineering simply the ex post facto verification process, or *solver,* of a problem which has already been developed by the architect? Or is the meat of engineering [materials, geometry, connections and configurations] a potentially untapped field for designers. What is the meat of design if not material? How do computational tools allow the designer to seriously dig, or spelunk, into the world of the material matrices and geometrical physics or form active structure?

Manuel DeLanda argues that the study of matter and its behavior, which in effect implies the study of geometry and configurations at the molecular and atomic levels, is the new field in which the sciences and the material philosophers should engage issues of nonlinearity, complexity, and dynamic systems of organization. DeLanda describes this type of complex emergent behavior from the philosopher's perspective, but it is clear how this applies to the designer.

> In other words, we are beginning to understand that any complex system, whether composed of interacting molecules, organic creatures or economic agents, is capable of spontaneously generating order and actively organizing itself into new structures and forms. It is

[15] Leach, Neil, Turnbull, David and Williams, Chris. Digital Tectonics. Chichester, West Sussex, U.K.; Hoboken, NJ : Wiley-Academy, 2004, p. 11.

> precisely this ability of matter and energy to self-organize that is of greatest significance to the philosopher.[16]

All of these systems are dependant upon basic feedback loop structures for their formations and adaptations.

Since we now understand that materials have dynamic and responsive properties we understand that designers must use material feedback in the configuration of form. Conventional design strategies apply form a priori to matter, without consideration for material desires and preferences. DeLanda describes this as a result of our "focus on linear and equilibrium behavior" that has created "a view of matter as *an inert receptacle for forms imposed from the outside*, a view with many similarities to Creationism and Platonism".[17] Deleuze calls this type of formal generation the ***Hylomorphic Model*** and writes that it:

> …assumes a fixed form and a matter deemed homogeneous. It is the idea of the law that assures the model's coherence, since laws are what submits matter to this or that form, and conversely, realize in matter a given property deduced from the form… [But the] hylomorphic model leaves many things, active and affective, by the wayside. On the one hand, to the formed or formable matter we must add an entire energetic materiality in movement, carrying singularities… that are already like implicit forms that are topological, rather than geometrical, and that combine with processes of deformation: for example, the variable undulations and torsions of the fibers guiding the operations of splitting wood. On the other hand, to the essential properties of matter deriving from the

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[16] DeLanda, Manuel. "Material Complexity," Digital Tectonics. Chichester, West Sussex, U.K.; Hoboken, NJ : Wiley-Academy, 2004, p. 17.

[17] Ibid, p. 18-19.

> formal essence we must add variable intensive affects, now resulting from the operation, now on the contrary, making it possible: for example, wood that is more or less porous, more or less elastic and resistant. At any rate, it is a question of surrendering to the wood, then following where it leads by connecting operations to a materiality instead of imposing a form upon a matter.[18]

The technique of teasing out formal configurations from material behavior through natural phenomenon [experimentation] is strongly displayed in the work of Frei Otto both through digital and analog computing. Otto studies materials and natural formations in order to derive design strategies. This approach is also clearly demonstrated in the classic example of Gaudi's inverted models. All of these techniques rely on the self-organizational behavior of matter taking a certain configuration while exposed to particular physical conditions, forces.

Today engineering know-how has been captured by software as a list of rule-based tasks. Through the power of computation complex systems can finally be studied with conviction. A deeper understanding of material behaviors and formal desires will no doubt reverberate loudly throughout the design world and could perhaps represent a major paradigm shift in design thinking. The dynamic behaviors of the virtual that have been so in vogue during the last decade could give way to dynamic materialities in the coming decades. This knowledge is now accessible to the designer for 'Ignorant Appropriations' and digital experimentations in design, analysis, and modification of the sort that Otto was doing with analog models. These experiments will now being undertaken in the virtual realm.

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[18] Ibid, p. 19.

CHAPTER 3 | CULTURE, TECHNIQUES AND OPPORTUNITIES

Cultural Implications

We now understand why we desire to develop new emergent design processes but we must ask the question of how to work within this context. What are the potentials of this process and how are those potentials related to larger cultural issues.

Ali Rahim has argued that technology is the cultural artifact of techniques. How do procedures effect the world and shape culture. How does, for example, the technique of exposing photosensitive film to light through a precision sculpted piece of glass change the global perception of representation. And conversely, how do shifts in cultural perception create the environment from which new techniques emerge. This paper claims that through the process of design through structural feedback architecture will gain a new mode of transparency by illuminating the invisible phantoms of physical forces. Just as the cathedrals of the middle-ages were themselves representations that created the collective conscience of a higher power and became symbols for the cultural paradigm of the day, architecture today can regain its cultural significance as a formo-material representation of the invisible physical forces which constantly surround us, thus bringing the Meta and the Atomic together as a singular representational reality. This is an architecture that speaks directly to the way in which we understand the world, and becomes a constructed positive reinforcement of contemporary scientific thought.

The Feedback Strategy

One basic premise of human understanding, and in fact the mythical origins of architecture, is the premise of physiological need. All organisms have need and this need becomes the primary driver for basic decision making, refer to Maslow's Pyramid. Needs are based on the physical behaviors of our material bodies. If my stomach is empty I'm in need of food. But what if I had no nervous system to alert my brain and my body that I need food and that I should take action. This is the basic function of the body's nervous system; to analyze need and help the skeletal-muscular system respond and react, i.e. to change states in order to satisfy needs. Once the body reacts and eats a cheeseburger, the need is satisfied and the process of need, analysis, and reaction is complete. This is a basic feedback loop that happens thousands of times throughout a single human life. However this is a cyclic loop where the state of the system is in the same general condition at the end of several cycles as it was when it started, perhaps only a little fatter.

The true potential for feedback loops in the design process is to create evolutionary progressions based on need. In this context needs can be predictable or unpredictable, but in either case these needs create design opportunities. The identification of those design opportunities becomes the basic goal of the process. The analytical tools have now framed a design problem where the designer can bring intuitive operations to bear on the geometry and materiality in order to satisfy the identified need. These evolutionary operations can be applied to global organizations and localized specialization of geometry and material through such techniques as folding, weaving, knotting, cutting, bending, stretching, compressing, et cetera. In other words, this is a type of Darwinian structural fitness test where geometric and material adaptations are the key to survival. Just as the human body has evolved both geometrically and materially over many millennium based on physical needs and environmental contexts the design of a building can evolve over many analytical-operative cycles. This machine-human loop is critical. The design process must not loose human intuition as a critical knowledge base. Chris Wise argues this point regarding design intuition in the article *Drunk in an Orgy of Technology*:

> …Because we can make new things, our aspirations for what we can have, what we can afford, what we know will work, will change. This is marvelous, an eye-opening process that should be nurtured. However, the key to the success of the whole caboodle is the human mind which…filters, edits, composes, interrogates and challenges. So I would like to advocate less algorithms, more responsiveness, less technological drunkenness and more direction. Less silicone-chippery, more brain. But I can't quite do it.[19]

Structural Ornament

The type of iterative geometrical intricacy that can be produced through this process can, in fact, be seen as structural ornamentation and can therefore also take us into the debate of ornament and culture, which would take us all the way back to the Guttae of the ancient Greek temples, blurring technique and representation.

Greg Lynn describes the potential for a new type of ornamentation, one which breaks from the classical notion of ornament as surface appliqué and one which

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[19] Wise, Chris. "Drunk in an Orgy of Technology." Emergence: Morphogenetic Design Strategies. New York: Wiley, 2004, p. 57.

embraces the resultant of intuitive procedures and technical expertise as that which produces contemporary ornamentation. ***Process*,** seen as a Deleuzian construct, is not necessarily at odds with ornamentation which is usually associated with representation. Process based ornamentation comes from the experience of the architect in applying the technique. If the argument here is to incorporate the techniques of structural analysis into the process of formo-genesis then structure must be seen as ornamentation and that which is ornament is in fact integral structure. Again we see a collapse of distinction. Lynn suggests that 'it is not just the expansion of structure into the field of ornament, or of ornament becoming structural, but rather a dependency on collaboration that transforms each category in some unforeseen and unprecedented way.'[20]

Lynn sees contemporary methods of modeling and manufacturing as that which produces ornamentation through representational and productional modes. One example of this is the ribbing effect produced through the translation of geometric surface into machining tool path as lines in space, or intricately articulated discrete segments as that which creates the continuums. This is again an articulation of ***the fold*** as that which is ***in-between*** discrete material entities. Lynn also describes this as a "smooth transformation involving the intensive integration of differences within a continuous yet heterogeneous systems. Smooth mixtures are made up of disparate elements which maintain their integrity while being blended within a continuous field of

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[20] Lynn, Greg, and Leach, Neil. "The Structure of Ornament," Digital Tectonics. Chichester, West Sussex, U.K.; Hoboken, NJ : Wiley-Academy, 2004, p. 65.

other free elements."[21] See the "Predator" project in Chapter 4 as an example of CNC fabrication producing ornamentation.

Neil Leach has described the nature of contemporary digital practice in architecture as having moved away from the classical notions of visual composition, proportion, and representation as the primary drivers in design and towards an architecture of the gothic. This architecture is based in experimentation as procedure, and material/configuration as medium. Is this perhaps a revival of gothic deep structure in the 21st century? DeLanda concludes his essay Material Complexity by stating that:

> …the historical processes of homogenization and routinization have promoted the 'hylomorphic schema' as a paradigm of the genesis of form. Conversely, it is partly thanks to the new theories of self-organization that the potential complexity of behavior of even the humbler forms of matter-energy has been revealed. We may now be in a position to think about the origin of form and structure, not as something imposed from the outside on an inert matter, not as a hierarchical command from above as in an assembly line, but as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create.[22]

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[21] Lynn, Greg. "The Folded, The Pliant, and The Supple," Folds, Bodies, & Blobs, collected essays. Bruxelles: La Lettre Volee, 1998, p. 110.

[22] DeLanda, Manuel. "Material Complexity," Digital Tectonics. Chichester, West Sussex, U.K.; Hoboken, NJ : Wiley-Academy, 2004, p. 21.

CHAPTER 4 | CONTEMPORARY CONTEXT

Several projects have been undertaken recently by some leading practitioners that are testing out this notion of using structural feedback as an integral part of the design process. Some of these projects approach the problem from the question of **structural surface** and other from a more conventional view of **structural system**.

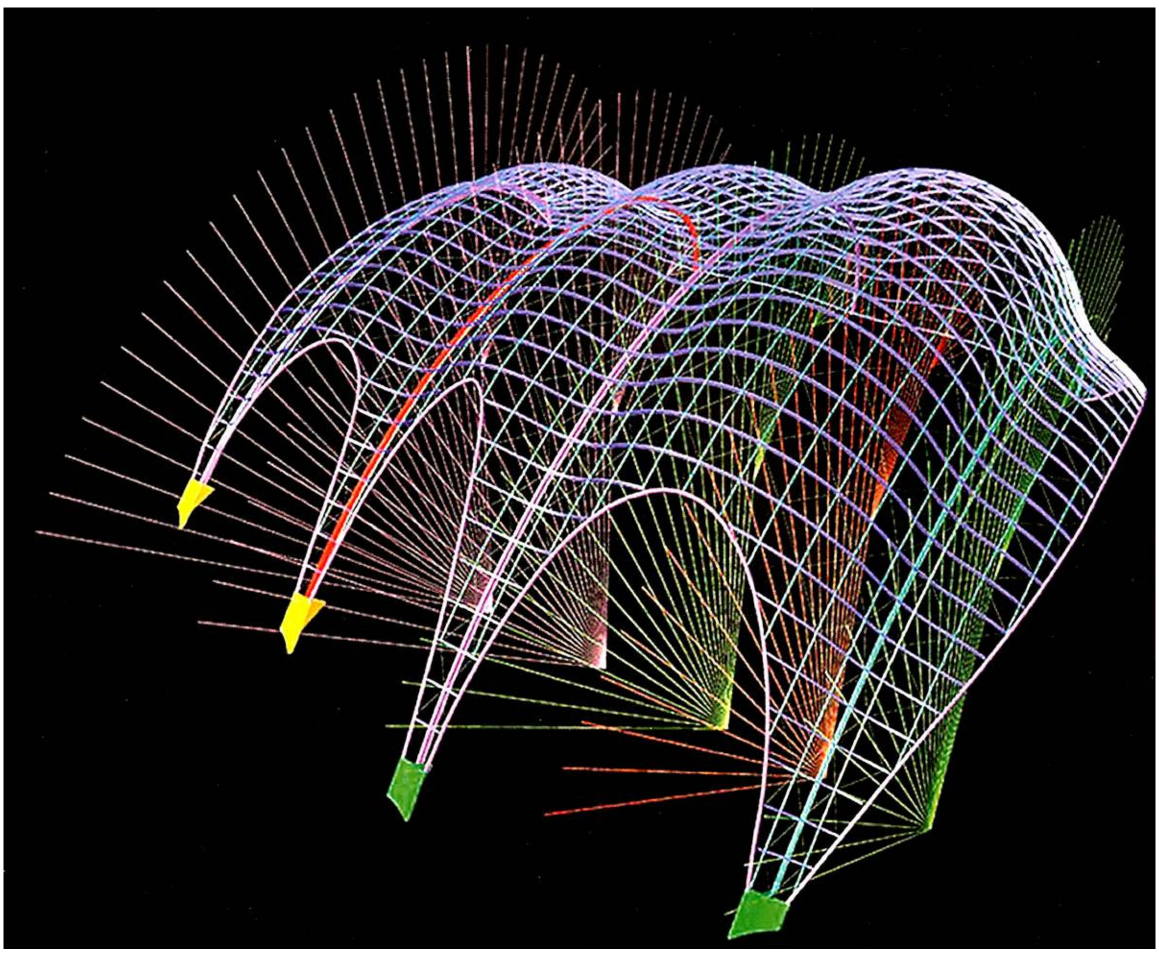

Figure 1 | Sage Music Center - Surface Geometry

Eifform - Amsterdam - 2002

This canopy installation produced in the courtyard of Amsterdam's Academie van Bouwkunst was designed through the implementation of a software called Eifform that was developed by Kristina Shea. The novelty of the project is completely embedded in the structure of the program. Eifform is a rule based formal generation package that incorporates structural behavior into the generative algorithm to produce iterative, optimized design solutions based on predetermined performance criteria. This approach considers structural behavior as equal to formal manifestation. Shea describes this novelty in relation to traditional design processes.

> Now, rather than manipulate form separately and then solve the structural sub-problem, well-formulated logical relations between form and structure are created using a structural shape grammar. A structural shape grammar can then be used to generate design topology and geometry, so that they can add, remove and modify primitives and their connectivity, while maintaining structural meaning.[23]

[23] Shea, Kristina. "Directed Randomness," Digital Tectonics. Chichester, West Sussex, U.K.; Hoboken, NJ : Wiley-Academy, 2004, p. 91.

The algorithm uses primitive instantiation and a process of structural optimization based on crystallization called simulated annealing to create designs which produce ‘structural efficiency, economy of materials, member uniformity, and even aesthetics’.[24] While the process of this project is slightly more automated than the process which is proposed by this paper it is clear to see the parallels in design thinking and the use of structural feedback in formal generation.

Figure 22 | Completed installation in courtyard

[24] Ibid, p. 93.

Figure 3 | Triangulated working model

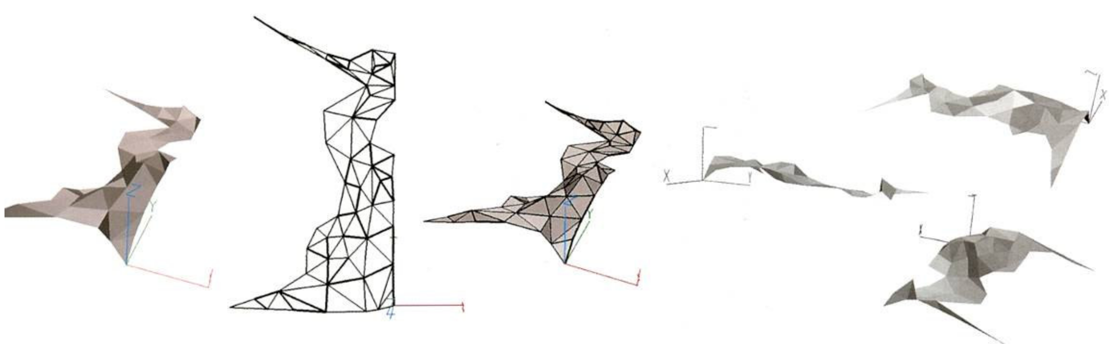

Figure 43 | Final iteration of the algorithm

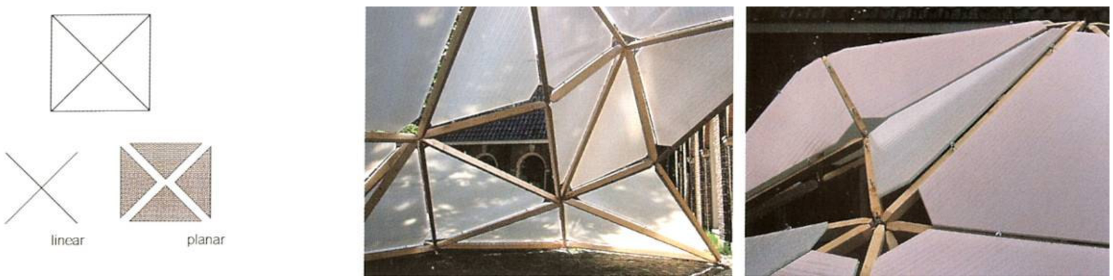

Figure 5 | Structural modules

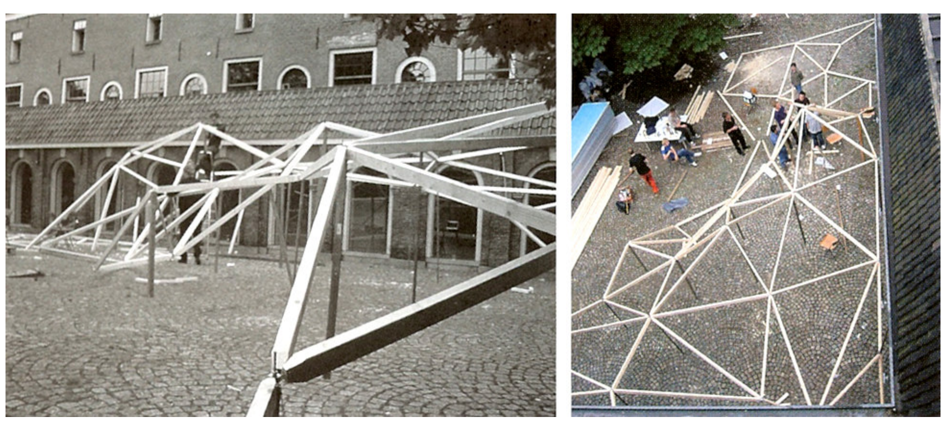

Figure 6 | Installation under construction

Predator - Columbus - 2001

This collaborative installation by Greg Lynn and Fabian Marcaccio is a form active space which capitalizes on the potential of the continuously ribbed surface as a primary structural system. MDF molds were CNC routed to produce the desired complex surface and then 4' X 8' polymer sheets were vacuum-formed to those molds to produce the final components. While structural feedback was not a driver for global geometry, it is clear to see how the notion of surface form, structure, and operation are developed simultaneously to produce a structural skin.

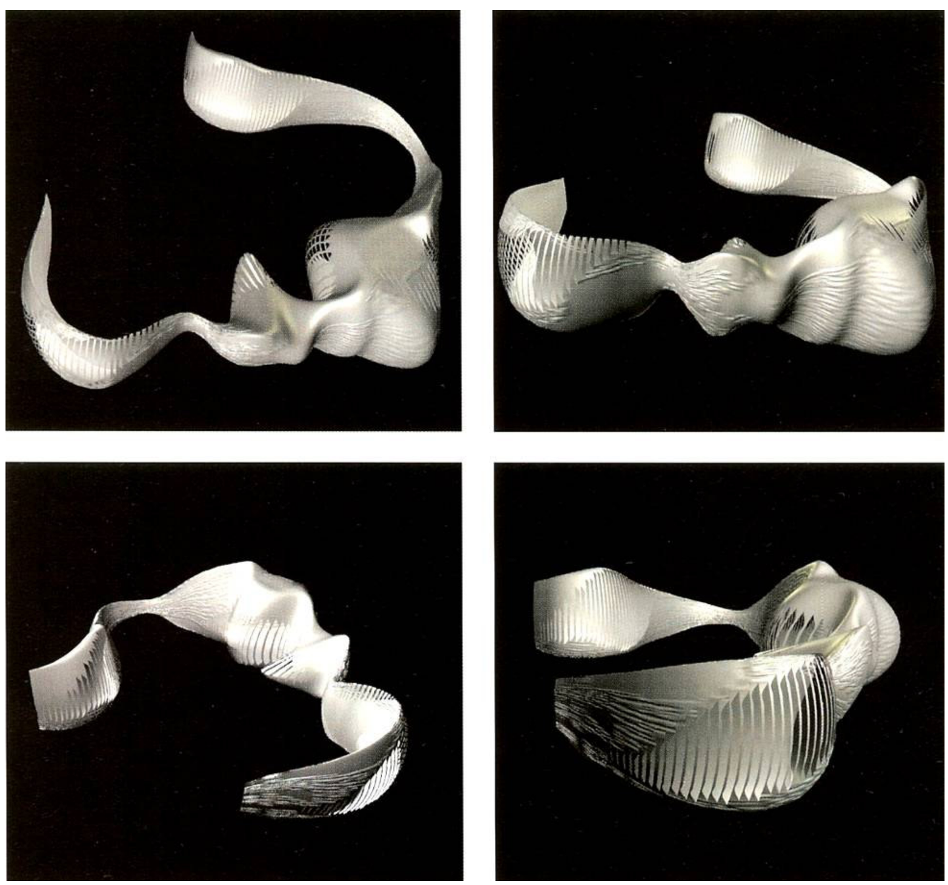

Figure 74 | Digitally modeled surface forms

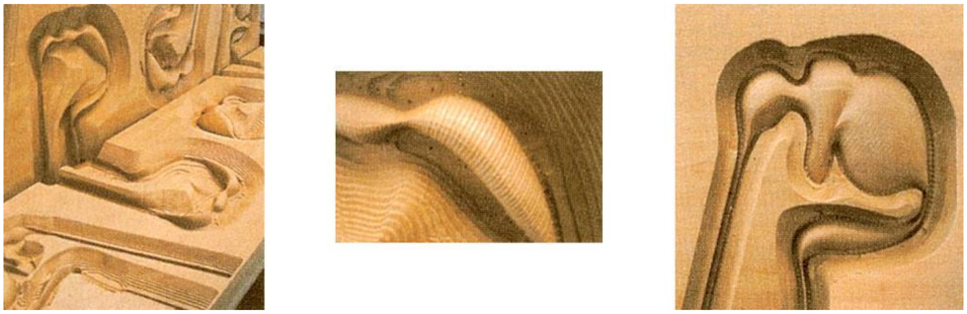

Figure 8 | CNC milled MDF formwork

Figure 9 | Installation of vacuum-formed polymer components at the Wexner Center

Habitation - Unrealized

In this design for a habitation, Ali Rahim and Contemporary Architecture Practice employee many generative techniques that capitalize on non-linear feedback loops to create form. Structural performance does not get reinput into the equation in order to manipulate global formal conditions but rather it is used to fluctuate localized thicknesses of material components. Computational Fluid Dynamics is used to calculate structural variability in order to produce a lean and efficient design which will reflect the cultural conditions of its conceptualization and construction.

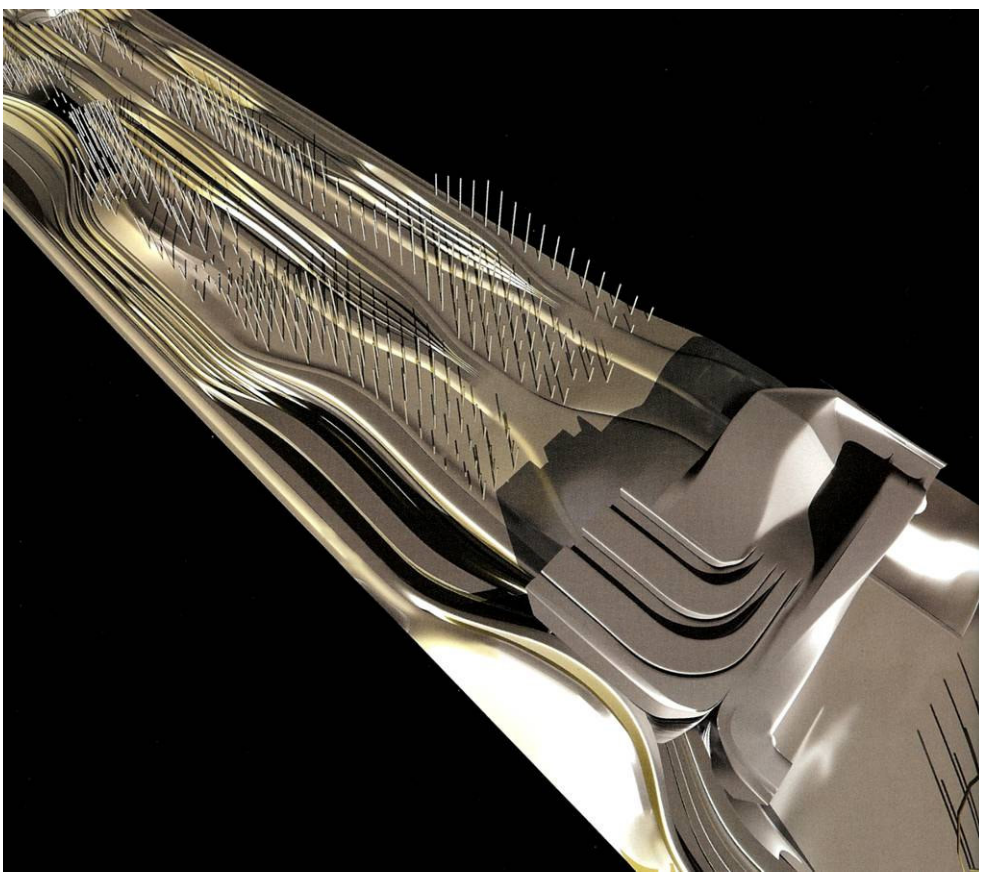

Figure 10 | Perspective

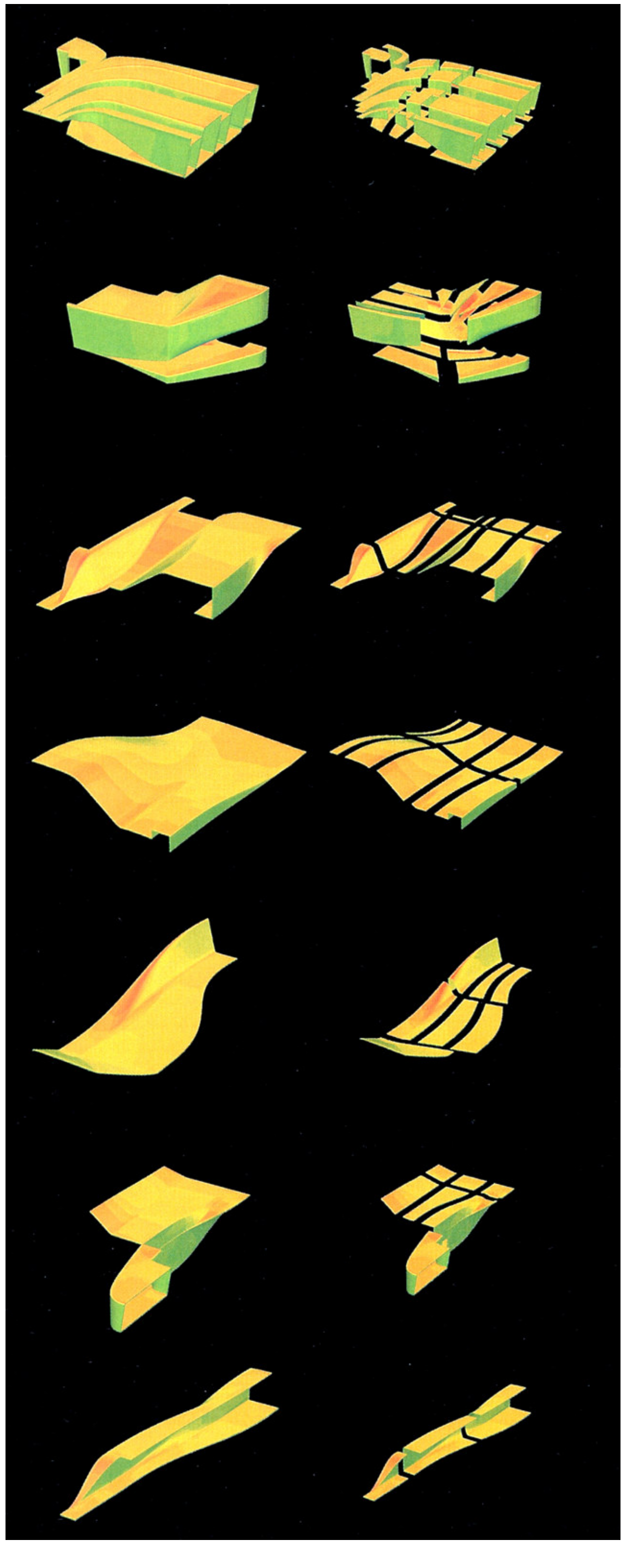

Figure 11 | Componentization of continuous surface

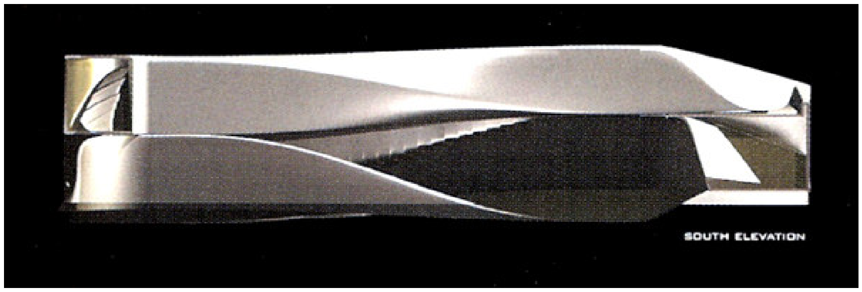

Figure 12 | South elevation of folded continuous surface

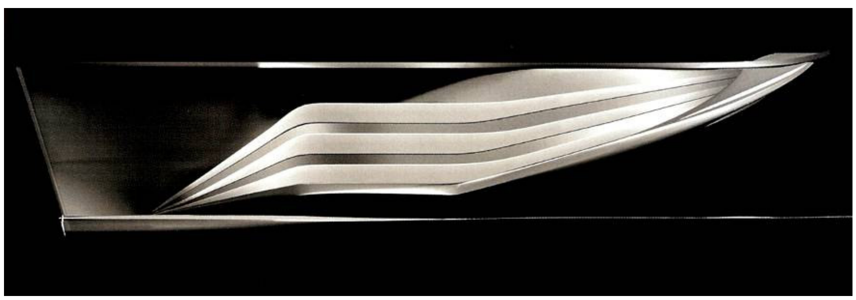

Figure 13 | Side elevation of folded continuous surface

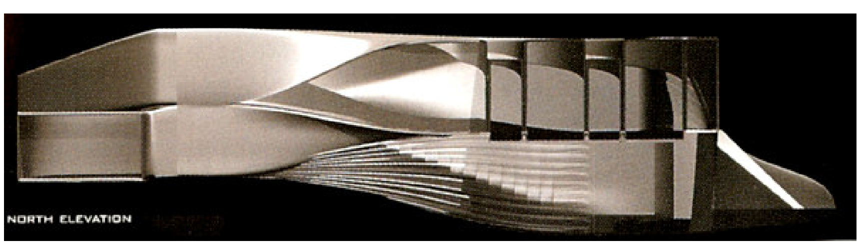

Figure 14 | North elevation of folded continuous surface

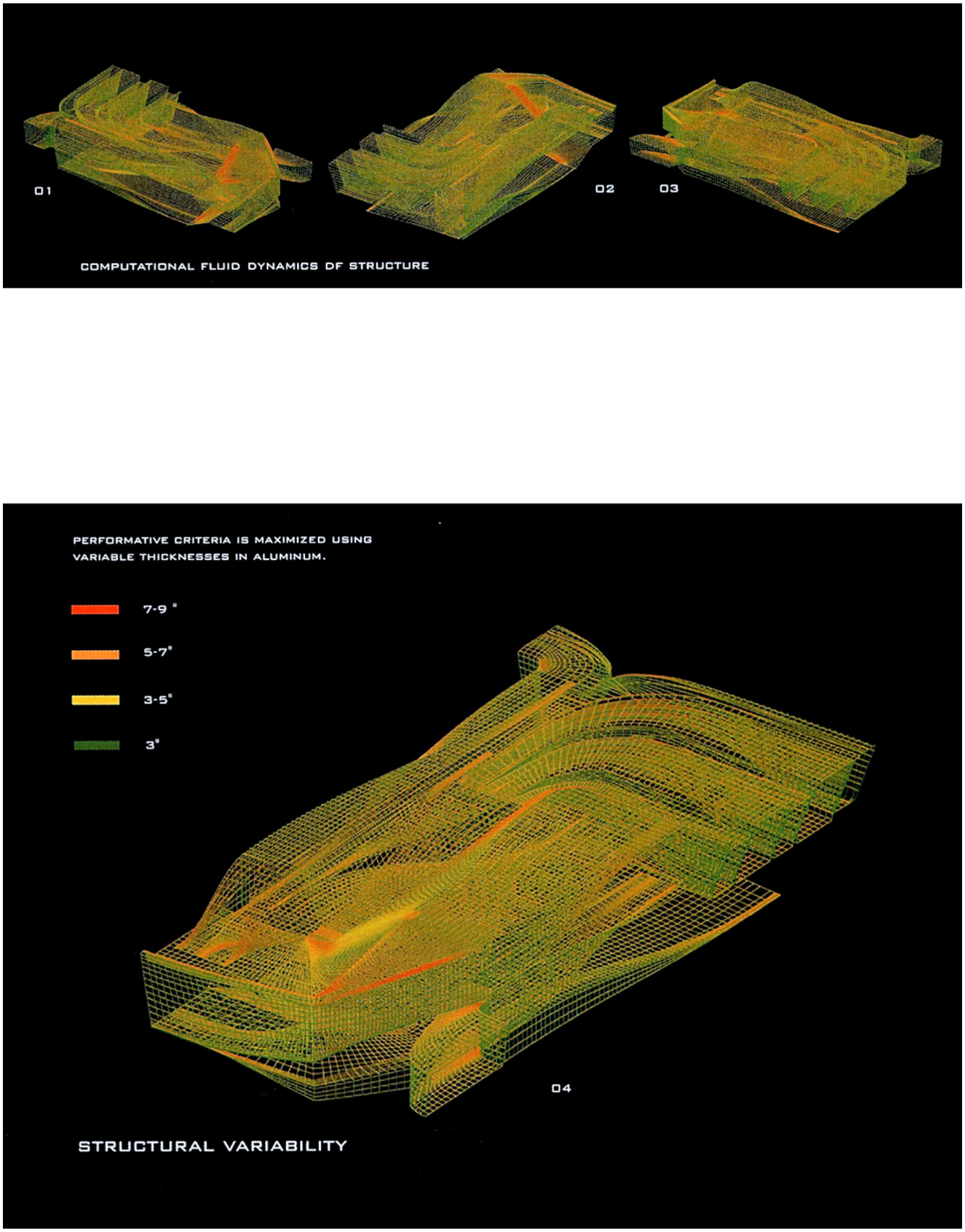

Figure 15 | C.F.D. model of structural variability

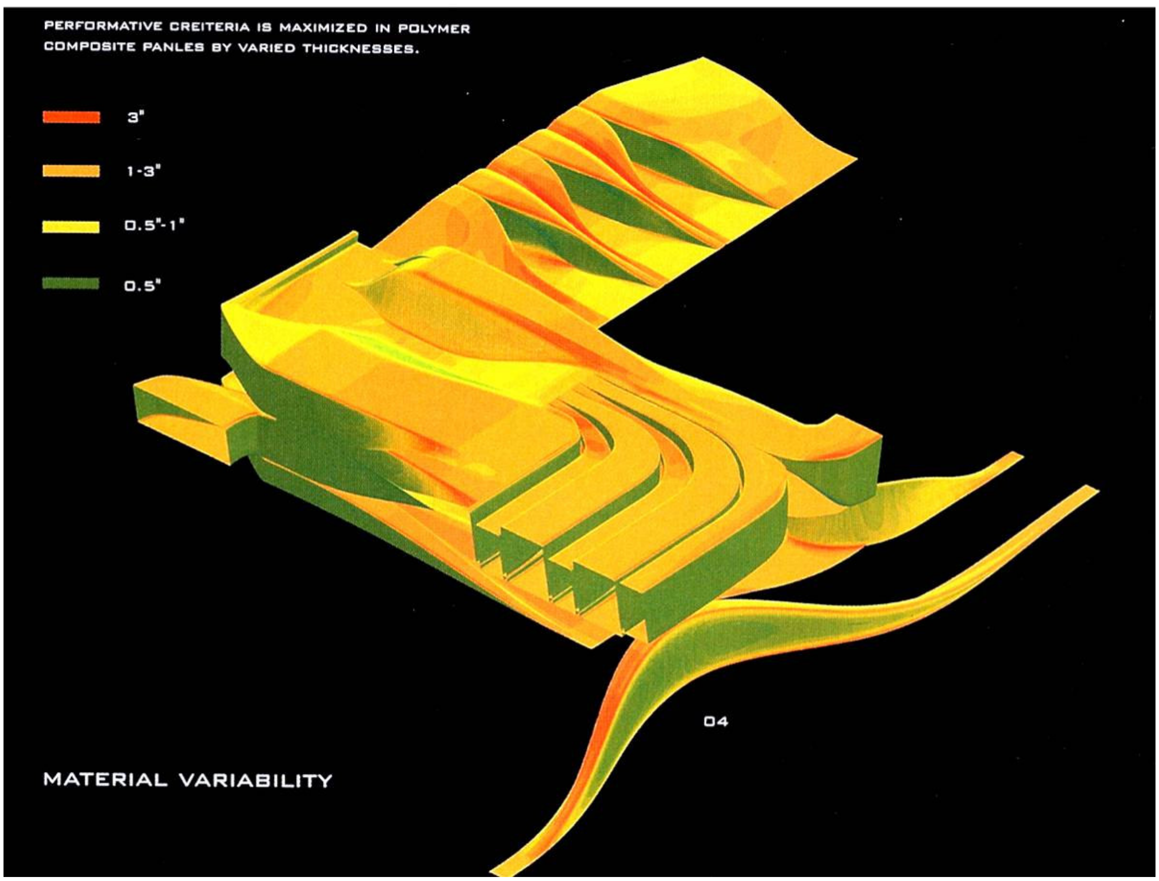

Figure 16 | C.F.D. model of material variability

Chavasse Park - Liverpool - Unrealized

This collaborative proposal by Cecil Balmond and Phillip Johnson for the Chavasse Park Project merged surface geometry, materiality, and performance from the outset. An algorithm was used to create a 3-Dimensional line which defined multiple 'strip' surfaces that ultimately created a singular structural shell. Material behavior and structural performance drove the development of an immaterial line into a structural skin. An iterative feedback loop was the primary procedural driver. Balmond describes the design process.

> In this method materiality comes immediately after the concept algorithm, rapidly modifying the three dimensional trajectory. It is not a simple sequence, but rather a constant interchange between concept and materiality as the work unfolds.[25]

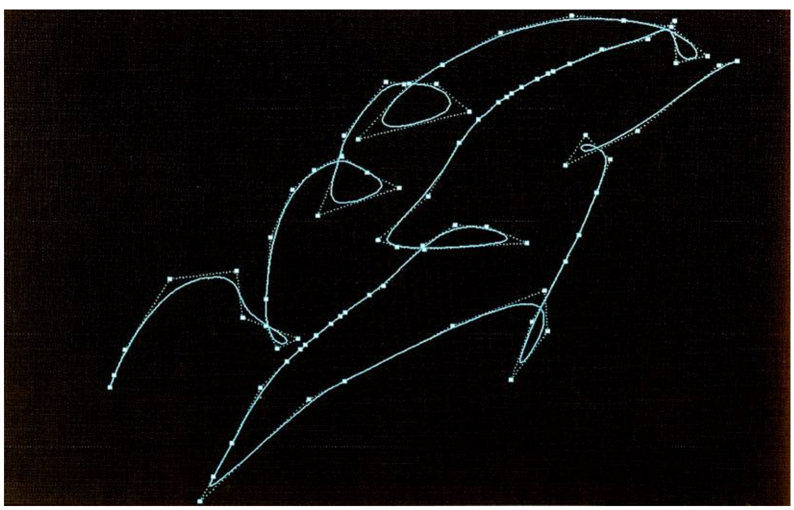

Figure 17 | Generative line algorithm

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[25] Balmond, Cecil. "The Digital and The Material." Contemporary Techniques in Architecture. London; New York: Wiley-Academy, 2002, p. 51.

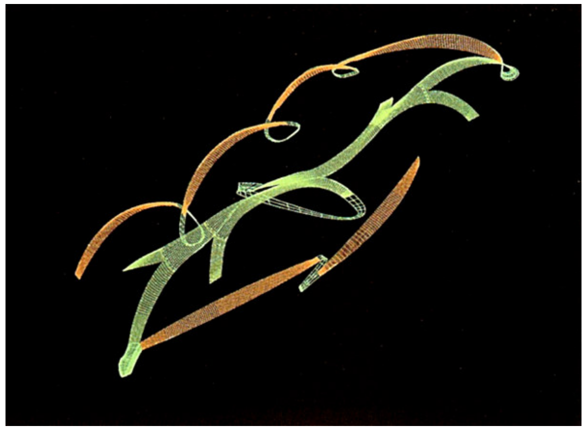

Figure 18 | Thick lines or strip surfaces

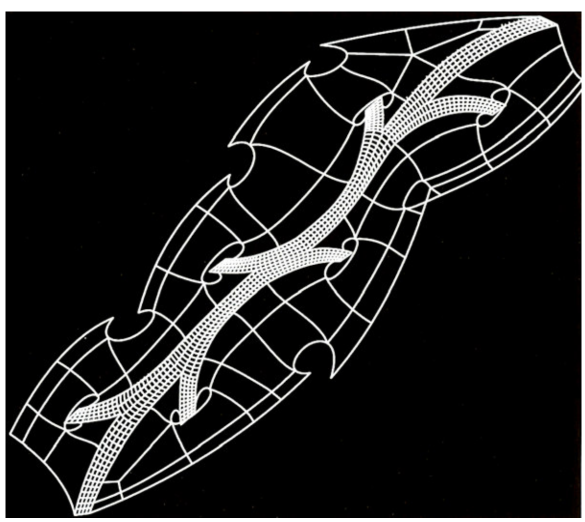

Figure 19 | Primary structural path

Figure 20 | Stress contour map

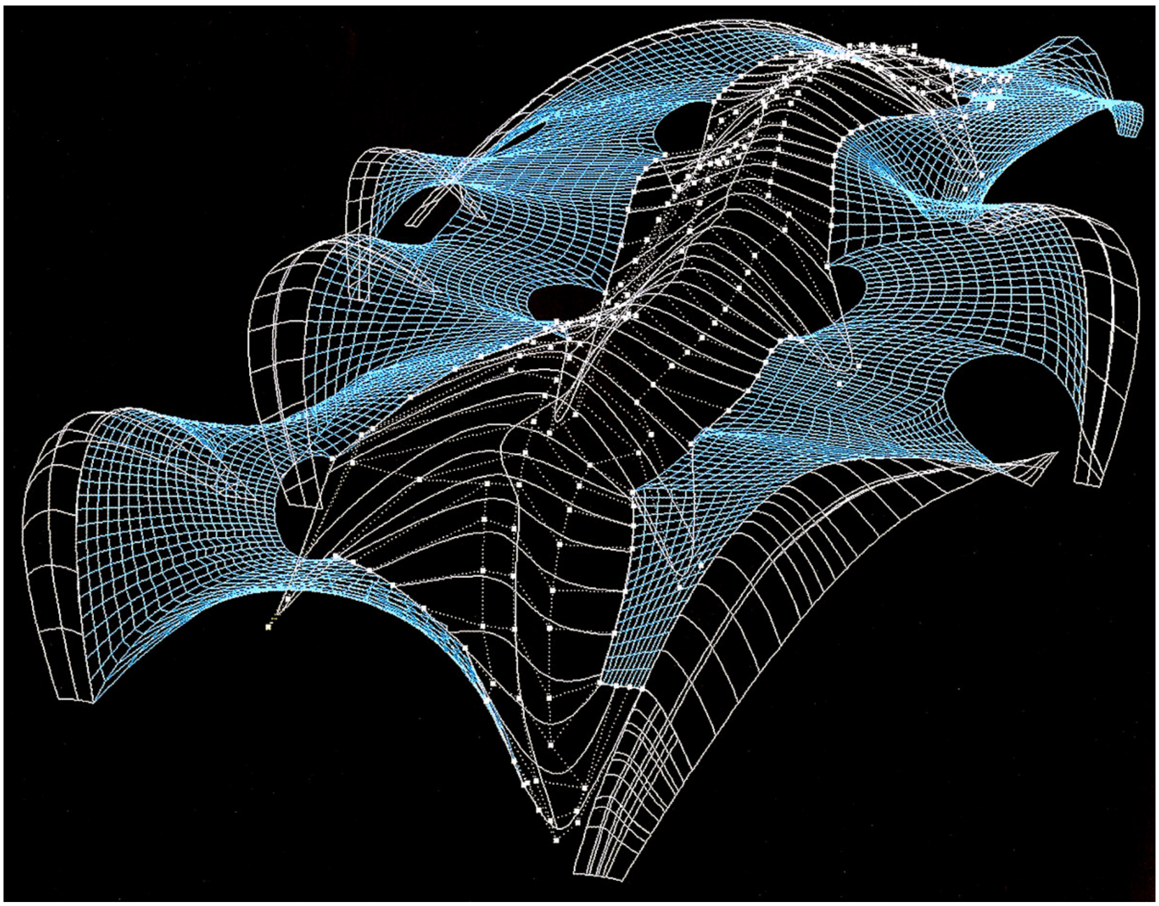

Figure 21 | Parametric analytical shell model

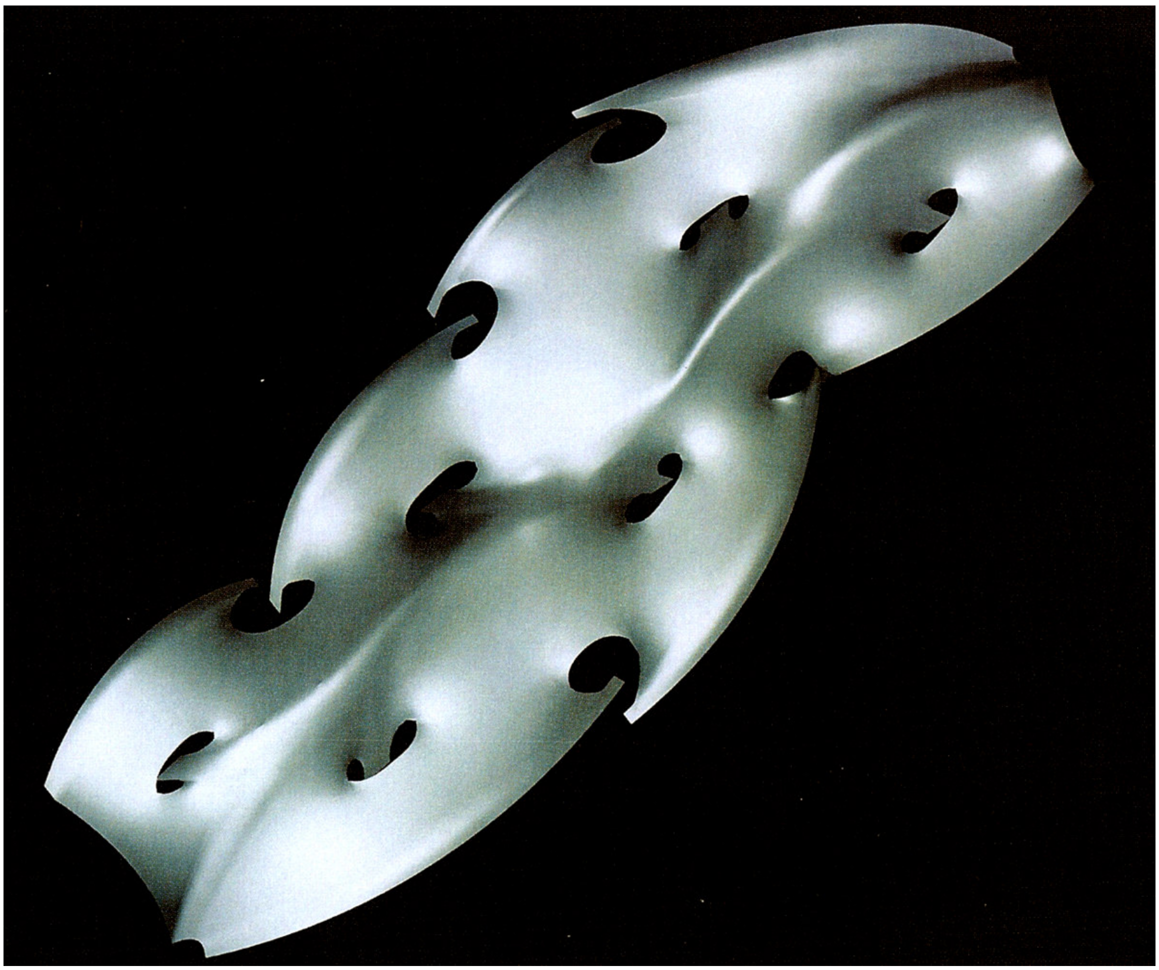

Figure 22 | Final structural skin

D-Tower - Doetinchem, Netherlands - 2004

This project for a sculpture gave Lars Spuybroek of NOX an opportunity to study surface and rib as an integrated structural system where primary forces are carried through a fiberglass membrane that has been analyzed using the ANSYS Finite Element platform. After the analytical design process CNC milled formwork was created to cast the fiberglass panels. This method allowed the analytical feedback to be applied during the construction process as a variable thickness surface, based on local and global stresses, through the application of various layers of fiberglass reinforcement.

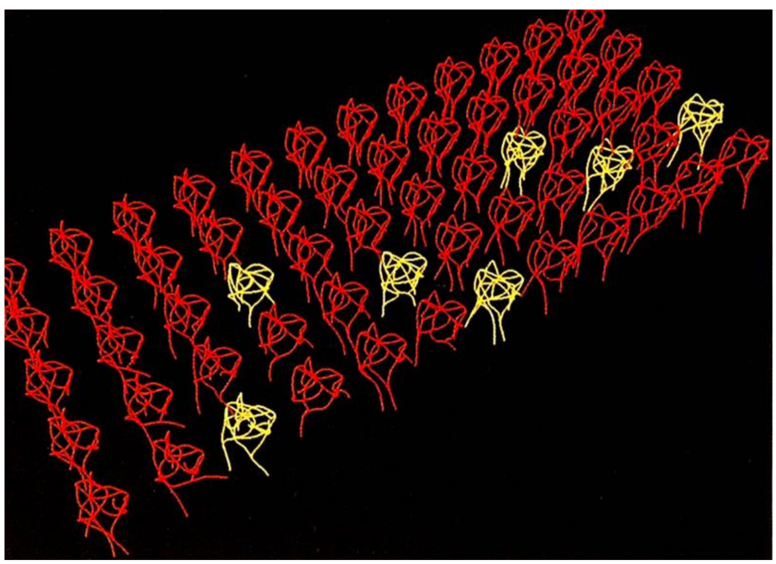

Figure 23 | Iterative formal studies based on line geometry

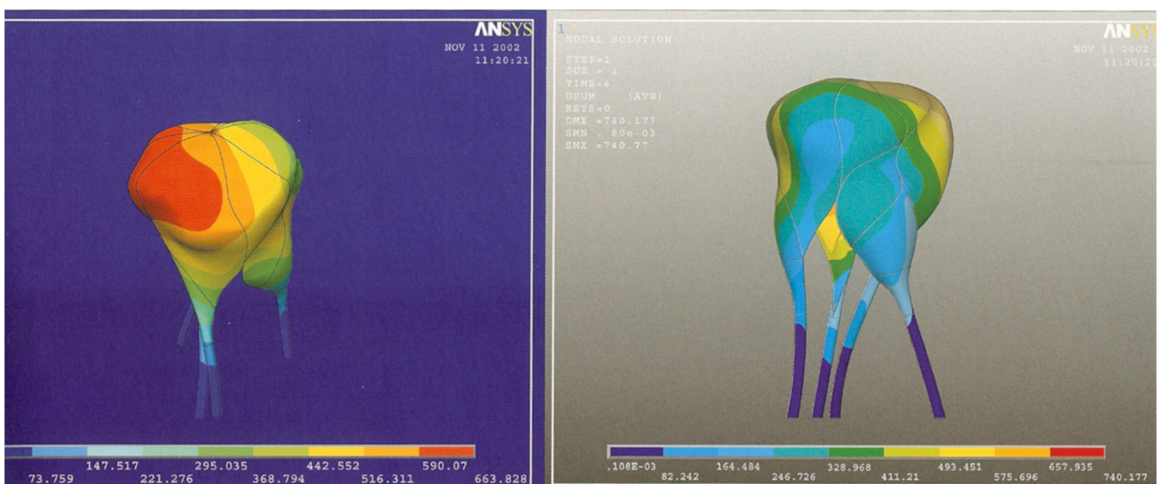

Figure 24 | FEA model of surface stresses

Figure 25 | Perspective

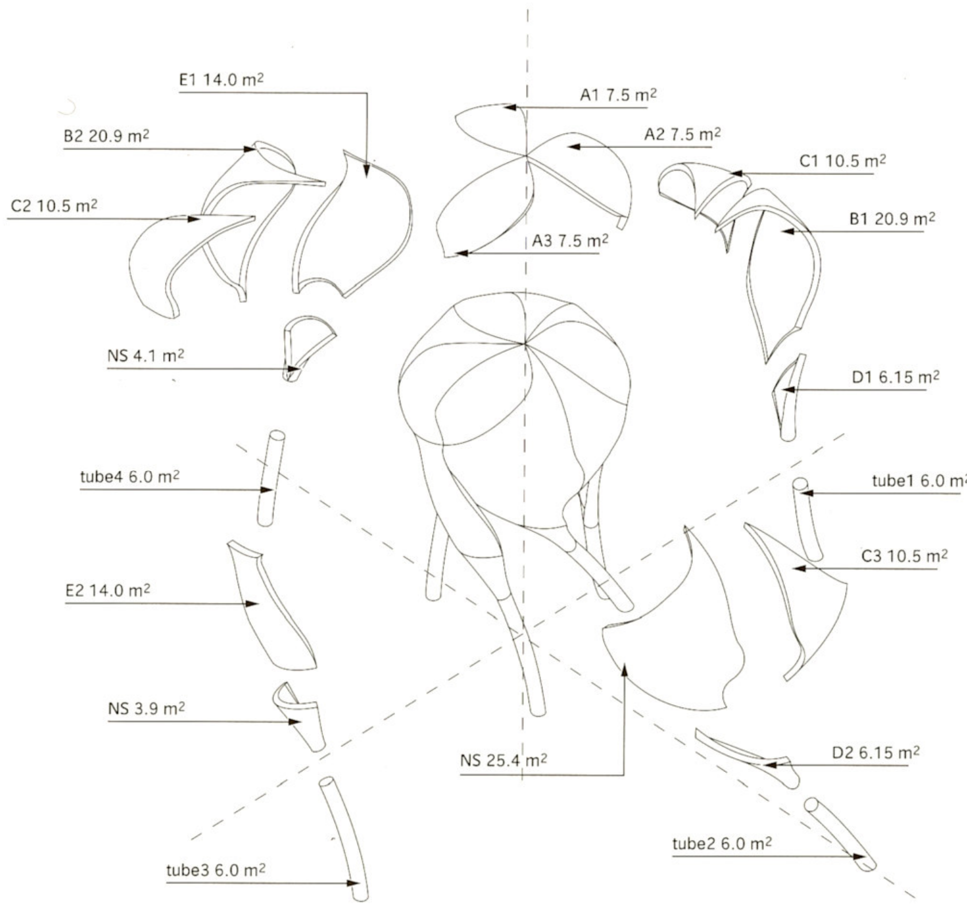

Figure 26 | Component diagram illustrating global symmetries

Figure 27 | CNC milled foam mold and fiberglass components

PART TWO | FINITE ELEMENT ANALYSIS

CHAPTER 5 | HISTORY & MOTIVATION OF FEA

Finite Element Analysis [from here forth referred to as FEA] is a mathematical method for analyzing the behavior of form and matter based on an approximate representation of a desired condition with topologically connected 1D, 2D, and 3D Finite Elements. This method was developed by the aerospace industry in the 1950's to replace the traditional method of 2D and 3D truss analysis that was originally developed in the 19th century for bridge design. Because the existing method of analysis assumed limited types of behavior it worked well for simple trusses and frames. However it was not suitable for complex forms because of the unpredictable nature of complex shapes. It would not be feasible to run analytical scenarios for so many possible deformed shapes. The advent of digital computing made the difficulty of analyzing complex 3D shapes possible through FEA. The Boeing Corporation was the first to successfully analyze a complex surface with an early version of FEA in the 1950's.[26]

The term 'Finite Element' was created by Dr. Ray Clough in 1956.[27] The development of the method was secretive and proprietary until NASA commissioned the development of the FE code that would be called NASTRAN. This code became the engineering standard in both the automotive and aerospace industry and was used as

[26] Adams, Vince, and Askenazi, Abraham. Building Better Products with Finite Element Analysis. Santa Fe: OnWard, 1999.

[27] Interactive Timeline - History Resources, American Society of Mechanical Engineers, New York, Viewed 05 July 2006, <http://www.asme.org/Communities/History/Resources/Interactive_Timeline.cfm>

the underpinnings for the development of many more FEA solvers in the 70's and 80's. NASTRAN is still a popularly used solver today.[28]

Originally FEA was a highly specialized engineering tool that was front-end intensive and computationally expensive. In the days of room sized digital computers FEA was reserved for analysis of things to be built by government agencies and large corporations due to the high cost and significant learning curve involved with building and analyzing a model. As computational power increased and costs decreased the technology become accessible to many smaller companies and analysis of everyday objects was feasible. By the 1980's FEA was so accessible that designers could then consider using FEA in the engineering design process. Interoperability protocols and standards were developed to translate geometry from CAD to FE pre-processors. IGES [Initial Graphics Exchange Specifications] and DXF [Data Exchange Format] became the standard file formats for geometry exchange. At this point there was still a significant amount of specialized knowledge in setting up FE models and so called ***Design Analyst*** were designated within companies to handle FEA work.[29]

FEA technology and accessibility has advanced significantly still since the 1980's. One popular text on FEA has described the current state of design and FEA in the following passage.

> …the PC platform has become a major force in high end analysis. The technology has become so accessible that it is actually being 'hidden' inside CAD packages. It is not uncommon for a product engineering

[28] Ibid

[29] Ibid

> company to have non-specialists performing nonlinear, vibration analysis, computational fluid dynamics [CFD], and multiphysics simulations. Models with 1 million degrees of freedom are being run on 'deskside' supercomputers capable of running 1 trillion operations per second. This means more computations in a second than ENIAC [first practical analog computer built in the 1940's] could have completed in over 650 years![30]

The primary motivation for using FEA is to make a reasonable prediction for the behavior of form and matter. One must always remember that all types of analytical engineering are approximations. This includes Finite Element Method. Depending on the level of resolution in the element approximation results will vary significantly. Regardless, this is still a powerful method for predicting behavior and studying design variations in an iterative manner. Current FEA packages have also simplified the results of analysis by converting the old text based output files into intuitive graphic mappings, behavioral animations, and many other types of result representations. This again helps the designer use analytical results creatively and intuitively.

Ultimately, FEA is implemented in a design process with the intent of building an object in the physical world and having it behave as desired and expected. Since we know that FEA is an approximate representation which is prone to both machine and human error, physical models [Rapid Prototyping] should always be built and tested to validate or invalidate expected behavior. One might ask then what is the point of doing the FEA at all. FEA and Rapid Prototyping complement each other well, each with its primary strengths and primary weaknesses. Rapid Prototyping is great for

[30] Ibid, p. 7.

communicating form and matter to extended audiences and is the only real validation of expected behavior in the physical world if built as a full representation of the finished assembly with proper materials and connections. However, rapid prototyping is still costly and time consuming and will ultimately only show you the results of the first failing components, or the weakest members. In other words, you may understand behavior at the point of failure but not throughout the entire system. Also Rapid Prototyping is usually built with an analogous material to the actual material and will therefore produce different results based on material properties. For example, a cornstarch and cyanoacrylate 3D printed model of a cantilevered reinforced concrete structure will behave quite differently under loading than will the actual structure. FEA on the other hand will produce global results for the entire system so that informed decisions can be made at both the global [macro] and local [micro] levels. FEA can also simulate material properties with great precision, given that the materials are isotropic and homogeneous. The disadvantages of FEA are its virtuality and learning curve. Communication through digital representations on the screen will never have the intuitive power of a physical representation. Additionally, even though FEA is becoming more and more accessible to the design world, it is still somewhat specialized knowledge and cannot be understood and implemented by the craftsman as with a physical prototype.

CHAPTER 6 | STRUCTURE AND PROCESS OF FEA

In a nutshell, a Finite Element Model is an assemblage of many mathematical entities [Finite Elements] as an approximate representation of geometry, material properties, connectivity, and their spatial relationships. This representation can then be used in conjunction with Boundary Conditions, which are simulations of real world physics, in order to analyze behavior by submitting the model to a solver and then viewing the results. The following is the general procedure for creating a FE model, analyzing it, and viewing the results for interpretation and design implementation.

In general FEA environments can be broken down into three discrete parts; pre-processor, solver, and post-processor.[31] Coming from the one-stop-shop mentality of CAD environments this can be quite confusing for a designer. A simple way of thinking about this is through the analogy of baking a cake. The pre-processor environment is analogous to the mixing bowl. This is where all the ingredients are dumped [imported], mixed [spatially arranged and connected], and eventually spread into their final form in the baking pan [given their constraints]. The batter then goes to the solver which is analogous to the oven. This is where the batter gets cooked and also where the FE input deck gets solved. Just as there are many different types of ovens, convection, steam, microwave, etc, there are many different types of solvers. But ultimately the cake gets cooked and the model gets resolved [this is a loose analogy, see note on solvers

[31] Ibid, p. 506-510.

below]. And lastly, what good is a cake if you cannot eat it. This is where post-processing enters. Post-processing is the expression and visualization of the analytical results, without which the whole process is useless.

For the purposes of this paper we are mostly concerned with the fluid translation of information from the design environment [CAD] to the analytical environment [FEA] and back again. This translation is critical to the usefulness of using FEA as an iterative design tool. In the past, FE models where built manually in a pre-processor environment or in a text editor. This was a time consuming, tedious, and error riddled process. Every node had to be manually input through coordinate definition and then elements created through nodal connectivity. One can easily see why complex forms would not be welcomed in this type of constructive environment. However, today algorithms have been created to automatically generate FE models from well formed CAD geometry, opening the door for designers to analyze complex form quickly and with less specialized knowledge.

The ability to translate data from CAD to FEA pre-processors using a standardized translation format first came in 1979 with the introduction of the IGES file format. Prior to the development of the IGES format translators were written for each FEA code individually. IGES was developed through the cooperative efforts of many organizations in order to have a neutral file format which would allow data exchange between proprietary systems.[32] Other neutral file formats soon followed, DXF being one

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[32] IGES Project, National Institute of Standards and Technology, Gaithersburg, Viewed 22 June 2006, < http://www.nist.gov/iges/>

of the most notable which was introduced in 1982 by Autodesk. Today there are numerous neutral file formats, including ACIS, STEP, and Parasolid which are commonly used to translate data between systems.[33]

The key to making this process successful from a CAD perspective is to have well formed, clean geometry that does not contain anomalous conditions. In addition to geometric fitness, CAD files should be well organized into layering schema which will aid in the meshing process down stream. In single body models this is less of a concern, but in multi-body models with connections this can be the difference between hours and days of pre-processor work. In multi-body, connected models all points of connection should be geometrically identified and organized into discrete layers in the CAD model. This will greatly simplify modeling connectors in the pre-processor. Lastly, helpers can be modeled in CAD to aid in a variety of pre-processor tasks. For example, lines can be created to establish vectors where loads will be generated in the pre-processor. In general, it is advantageous to create as much geometric and spatial information within the CAD environment as possible because pre-processors are still quite clumsy in comparison.

Once CAD geometry has been imported into the pre-processor the model should then be organized into component layers, material properties, and Boundary Conditions. Once the basic organizational schema has been built meshing can begin.

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[33] Adams, Vince, and Askenazi, Abraham. Building Better Products with Finite Element Analysis. Santa Fe: OnWard, 1999, p. 188.

As mentioned earlier, developments in automeshing techniques have been one of the key factors in making FE a viable design tool. Automeshing is the procedure by which raw surface or solid geometry may be translated into a variety of different 2D shell/plate elements or 3D solid elements. The elements can be of either first order or second order type, each containing up to 20 independent nodes. Second order elements generally give better results but are more computationally expensive. Automeshing maps elements to geometry and creates a single collector [layer] which is organized as geometry and elements. The retention of this relationship between the element and its originating geometry is critical for a variety of reasons including the ability to refine the mesh of elements and for mapping connectors and loads.

Automeshing often needs to be refined in order to obtain high quality results for final engineering checks. However, for initial design analysis most automeshing algorithms yield acceptable results. For our purposes here we will only deal with the meshing of 2D shell elements which are analogous to thin surface structures.

Once the meshing is done, property attributes for elements and materials should be defined. For 2D shell elements the most important property to define is the virtual thickness. In addition, most solvers require the user to give instructions on how to deal with elements as either shells [2D] or solids [3D]. Material properties must then be defined and mapped to the proper elements. Most linear static FE analyses define materials as being homogeneous and isotropic. Other material properties such as Modulus of Elasticity and Poisson's Ratio must also be defined.[34]

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[34] Ibid, p. 222.

The final step in setting up the model in the pre-processor is the creation of Boundary Conditions, from here on referred to as BC's. BC's are where loads [forces] and fixing points [constraints] are defined within the model. Loads can consist of many different types of forces; points loads, pressures, accelerations, moments, etc, and are all applied directly to individual elements. This study will focus primarily on point loads and uniform loads of a constant velocity. This loading schema will be representative of gravity and wind loads. Constraints are the global reactions, or in other words, how the model is fixed in space. Constraints are defined by the element of attachment, a position in space, and most importantly by their Degrees of Freedom [DOF]. Every constraint has six DOF, three translational and three rotational. For every constraint each DOF is independently controlled. Once the model has been fixed and a variety of forces has been applied Load Steps, or Load Combinations, are created. Load Steps allow for multiple loading permutations to be solved for a single stiffness matrix.

Now all the ingredients are mixed and ready for the oven. At this point an input deck is written out from the pre-processor and then submitted to the solver for analysis. As could be expected all solvers are not equal. Different solvers compute in different ways and should be used for different types of analysis. Deciding on the type of analysis to be performed is critical to choosing a solver. Before choosing a particular solver one must first ask the question, 'what is the question being asked by this analysis'. Once the analysis is complete the solver will output a results file based on the results that were requested from within the pre-processor. This results file is then read into the post-processor for visualization and results analysis.

For the engineering analyst this is the end of the line. For the conventional architect this line does not even exist. But for the hybrid Architect-Engineer however, this is the point in the process where feedback is gathered, considered, and reflected upon. From here the synthesis of design concept and physical behavior meet and go for another round.[35]

[35] Working method described from Altair Engineering Hypermesh Training Workshop, June 2006, Troy, Michigan.

PART THREE | DESIGN EXPERIMENTATIONS

CHAPTER 7 | PROJECT OBJECTIVES, CRITERIA, AND PROCEDURES

FEA is capable of analyzing many different types of scenarios and behaviors including temperature gradients, acceleration, vibration, and many others just to name a few. Most of these analyses are beyond the scope of what an architect might be expected to understand. So what good then is FEA to the architect if the results are neither comprehensible, applicable, nor implementable? In order for the process of design, analysis, and feedback to be productive, set criteria must be established for the architect to react against. These criteria should be intuitively comprehensible and must also be highly generative. The two primary feedback criteria to be used in this process are material stresses and shape buckling. Displacement is a third criterion to be considered when applicable, normally when shapes with stable post-buckling curves are used. Material stresses and shape buckling modes will be analyzed using vertically loaded shell structures to predict behavior and search for design opportunities. The loading scheme to be used will be a 60 pounds per square foot gravity load, which is generically derived from a 40 pounds per square foot live load and 20 pounds per square foot dead load. Lateral loads will not be considered in these analyses for the sake of simplification. This loading scheme is somewhat arbitrary as this exercise has no architectural program, but rather it is meant to be a reference for one type of real world structural loading scenarios.

Analysis of material stresses are important in order to ensure that the limit state of the material is not exceeded so that formal rigidity is retained. A safety factor of one-half the material limit state is normally used in designing for stresses. For ductile materials such as steel the limit state is usually defined by the yield point.

Displacements are normally the small amount of movements that occur in a structure when loaded that can also be recovered when the load is removed. In most structures displacements are not perceivable. In form active structures displacements may be large and even intentionally designed into the structural scheme. Standard linear-elastic FEA is not able to analyze this type of movement. Special non-linear analysis is used in such cases. Buckling behavior is described in the next section.

Shell structures can also be considered as membrane structures, which can be seen throughout nature as one of the most efficient structural systems. This system capitalizes on the multidirectional distribution of forces acting axially through a surface both in tension and compression. Membranes can be any type of surface having continuous connectivity. Webster's defines a Membrane as 'a thin pliable layer of tissue covering surfaces or separating or connecting regions, structures, or organs of an animal or plant'. However, structural membranes in architecture are normally formed into 3-Dimensional surface shapes that are capable of resisting loads. By giving a 2-Dimensional plane some amount of 3-Dimensional shape enormous resistance to force can be achieved. An egg shell is an excellent example of a shaped membrane which can carry tremendous loads in relation to its thickness.

> Shell surfaces are efficient, because, due to curvature, they are capable of propagating the load acting on the surface mainly by a sort of membrane action acting through the entire surface. This causes all the material to be more evenly stressed in compression and tension with

> little bending moment. The shell structure hence intrinsically derives its strength from its shape.[36]

See Chapters 8 and 9 for examples of form active structural performance.

In general, architectural shells can be defined as any surface membrane that is curved out of plane and capable of carrying significant loads. There are two types of out of plane curved surfaces, one-way single curvature, and two-way double curvature. Singly curved surfaces are also called ruled-surfaces or developable surfaces and are defined by curvature along a single straight axis. A common example of single curvature can be produced by pulling one corner of a sheet of paper out of plane without creasing or folding along a line. Doubly curved surfaces come in two types, synclastic and antisynclastic, and are defined by some curvature along any other curved trajectory. Synclastic doubly curved surfaces are composed by two curvatures in the principle axes that have positive curvature on the same side of the surface. Conversely, antisynclastic doubly curved surfaces are composed by two curvatures in the principle axes that have positive curvature on opposite sides of the surface.[37]

The three primary classifications of shell membranes in architecture are the singly curved barrel vault, the doubly curved synclastic sphere, and its component semi-sphere or dome, and the doubly curved antisynclastic hyperbolic paraboloid, of which

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[36] Benjamin, B.S. Structures for Architects. New York, N.Y.: Van Nostrand Reinhold Co., 1984, p. 334.

[37] Ibid

there are many different derivations. The study here will begin with the global form of a dome, but will ultimately attempt to employee all three types of curved surfaces to achieve structural skins.

Membranes, Stresses, and Buckling

Membranes are often thought of in architecture as taught coverings stretched across some type of armature. This spatial-structural scheme can be seen across the board from Native American Teepees to the giant shading roof structure at the Hajj Terminal of the Jeddah Airport in Saudi Arabia. This type of membrane is ultra thin and only capable of carrying tensile forces, with compressive forces being carried through the armature. The objective in this project is to be able to design fully independent structural surfaces which can stand on there own without being stabilized by a secondary system. In order to reach a state of equilibrium all systems must have a balance of forces, therefore in order for a structural skin to perform it must be able to carry compressive loads.

Compressive loads create two types of failure, crushing failure and buckling failure. In general crushing is a stress issue which can be accommodated through material properties and dimensionality. Stress is defined as a unit of force per unit area. For example 10 Pascals are equal to a force of 10 newtons applied to 1 square meter. Analysis of stresses therefore becomes a primary mode of selecting materials with particular properties and in determining material thicknesses. The FE model can give stress values back to the designer as a colored contour plot of the stresses in the surface when the system is loaded. Stresses are fairly easy to analyze and accommodate. This project will use Von Mises Stress as its element stress metric. Von Mises Stress ‘is calculated by combining stresses in two or three dimensions, with the result compared to the tensile strength of the material loaded in one dimension’.[38] The real difficulty with surface-active forms is in buckling behavior.

Buckling is the phenomena of an object under compressive forces to give way and drastically change its shape. It is caused by an instability in the structure based on shape. According to one source, ‘buckling involves lack of stability in a structure subject to compressive forces. This instability is independent of material strength and dependant on the structure’s shape’.[39] The Guide to Stability Design Criteria for Metal Structures describes this instability in the following paragraph.

> Instability is a condition wherein a compression member loses the ability to resist increasing loads and exhibits instead a decrease in load-carrying capacity. In other words, instability occurs at the maximum point on the load-deflection curve.[40]

Accommodation for column buckling is a typical design criterion which can easily be accounted for by governing the column’s slenderness ratio. In form-active structures however, buckling is not so easy to predict and accommodate. Imagine the sudden and

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[38] Von Mises Stress, Wikipedia, Viewed 01 July 2006, <http://en.wikipedia.org/wiki/Von_Mises_stress >

[39] Adams, Vince, and Askenazi, Abraham. Building Better Products with Finite Element Analysis. Santa Fe: OnWard, 1999, p. 465.

[40] Galambos, Theodore. Guide to Stability Design Criteria for Metal Structures - Fifth Edition. New York: Wiley, 1998, p. 13.

violent deformation that an aluminum soda can will undergo when loaded axially with enough force. This type of buckling behavior exhibited by the soda can could potentially be avoided by introducing shape-stiffening formal operations into the basic cylinder.

Buckling phenomena can be explained and predicted by using stress values to formulate an Eigenproblem. Eigenproblems yield Eigenvalues and Eigenvectors.

> The eigenvalues are the load multipliers that (along with the original loading pattern) describe the load level at which the structure buckles. The eigenvectors give the pattern of displacement of the structure as it buckles. The eigenvectors are only a visual pattern of the displacement – the magnitude of this pattern cannot be determined and it is generally considered to be infinite – that is, the onset of buckling is a catastrophic failure of the structure.[41]

Many FEA codes will run Eigenmode buckling scenarios and will predict shape deformation behavior. Predicting the mode of buckling and the Critical Load at which buckling begins is key to helping the designer make modifications in the design shape to resist this behavior. Buckling can occur locally in the form of ripples and bulges or globally in the form of deformation, displacement, or failure.

Buckling behavior also produces a unique condition called Bifurcation Buckling. This is the phenomena of particular shapes to either get more stiff or less stiff after initial buckling begins. Shapes which become more stiff are said to have stable post-buckling curves, while shapes that become less stiff are said to have unstable post-buckling

[41] **Dr. Russell Gentry, Associate Professor, Georgia Institute of Technology, comments on buckling behavior, July 9, 2006.**

curves.[42] Shapes with stable post-buckling curves will ultimately have material failure once the maximum load is reached. Theodore Galambos describes this behavior.

> Problems in instability of compression members can be subdivided into two categories: those associated with the phenomenon bifurcation of equilibrium, and those in which instability occurs when the system reaches a maximum, or limit, load without previous bifurcation. In the first case a perfect member, when subjected to increasing load, initially deforms in one mode and then, at a load referred to as the critical load, the deformation suddenly changes into a different pattern. Axially compressed columns, plates, and cylindrical shells experience this type of instability. By comparison, members belonging to the latter category deform in a single mode from the beginning of loading until the maximum load is reached. Shallow arches and spherical caps subjected to uniform external pressure are examples of the second type of instability.

Shapes with stable post-buckling curves could be used in dynamic designs where structures are intentionally allowed to move into stronger positions as loading increases. Shapes with unstable post-buckling curves would be desirable in static structures where the allowable loading is significantly less than the Critical Load. Stable post-buckling shapes are considered to be strain-hardened, that is, as the strain increases so does the strength.

Once initial shapes have been loaded and a buckling analysis has been run the results of the analysis can be read by the designer as feedback for modifications. Areas of large deformation would require the most shape-stiffening operations and therefore would present design *opportunities*. These shape-stiffening operations can come in the

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[42] Galambos, Theodore. Guide to Stability Design Criteria for Metal Structures - Fifth Edition. New York: Wiley, 1998, p. 16.

form of folds, bulges, knots, subtractions, and many other techniques. This is where design intension and designer's intuition come into play.

CHAPTER 8 | EXERCISE 1:

SINGLE CURVATURE PLATE WITH APPLIED PARALLEL FORCES

The exercises in Chapters 8 and 9 serve two purposes. First they are an opportunity for the author to become more familiar with the procedures for creating, analyzing and viewing the results of a FE model within a simplified context. Second, they test formal conditions that could be used as design operations, bending [single curvature] in the first case and bulging [double curvature] in the second case, to see what type of behavior a designer might expect from such conditions. This is not meant to be an exhaustive study, but rather the beginnings of a shape-structure-operation vocabulary for the hybrid architect-engineer.

This first exercise is testing the behavior of a plate at different aspect ratios as it gradually transforms from a plane to a singly curved surface [a cylinder] with an in-plane force applied symmetrically to the top of the plate. Each model was analyzed for buckling modes and Von Mises stresses and is shown as a colored contour plot with deformed geometry over the original undeformed shape shown as a wireframe. The deformed geometry has been exaggerated to emphasize the formal behavior.

Three plates having aspect ratios of 1:1, 1:2, and 1:4 were modeled as extrusions of a line, a shallow curve, a deep curve, a semi-circle, and a circle, see figure 28 below. These models were converted to FE shell elements and given thin wall properties for the shell and mapped to mild steel material properties. The wall thickness was modeled at 1/500 the overall width to emphasize potential buckling. Each condition was modeled once with fixed base constraints [0 DOF] and once with a pinned base constraint [3 DOF].

Table 1: Table of units used in FE model - Scheme A

LENGTH UNIT	METER
TIME UNIT	SECOND
MASS UNIT	KILOGRAM
FORCE UNIT	NEWTON
YOUNG'S MODULUS OF STEEL	210.0E+09
DENSITY OF STEEL	7.85E+03
YIELD STRESS OF MILD STEEL	200.0E+06
ACCELERATION DUE TO GRAVITY	9.81
VELOCITY EQUIVALENT TO 30 MPH	13.4
STRESS	PASCAL
DISPLACEMENT	METER

Table 2: Table of units used in FE model - Scheme B

LENGTH UNIT	MILLIMETERS X 10^-6
TIME UNIT	SECOND
MASS UNIT	KILOGRAM
FORCE UNIT	NEWTON
YOUNG'S MODULUS OF STEEL	210.0E+09
DENSITY OF STEEL	7.85E+03
YIELD STRESS OF MILD STEEL	200.0E+06
ACCELERATION DUE TO GRAVITY	9.81
VELOCITY EQUIVALENT TO 30 MPH	13.4
STRESS	MICROPASCAL
DISPLACEMENT	MILLIMETERS X 10^-6

The all of the following exercises were modeled in Rhinoceros 3.0, pre-processed in Altair's HyperMesh 7.0, analyzed using Altair's integrated Optistruct solver, and post-processed in Altair's Hyperview 7.0 This FE package is unitless and requires a consistent set of units in order to perform proper analysis. Table 1 above is a set of consistent units that are suggested for use in the LS-DYNA user's guide. Table 2 is an alternate set of consistent units. The units from Table 2 were used for this exercise. Buckling factors [Eigenvalues] should be multiplied by 10^{-6} for the proper Eigenvalue.

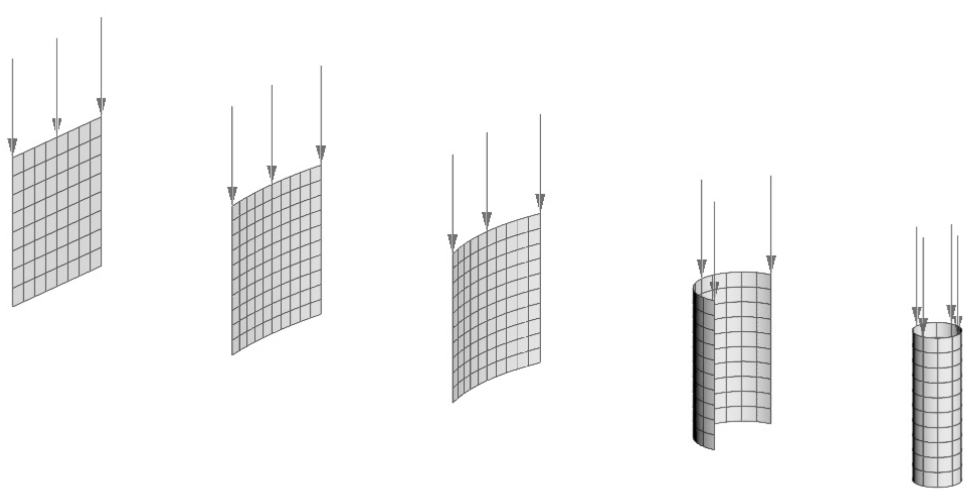


Figure 28 | Plate shape and loading scheme

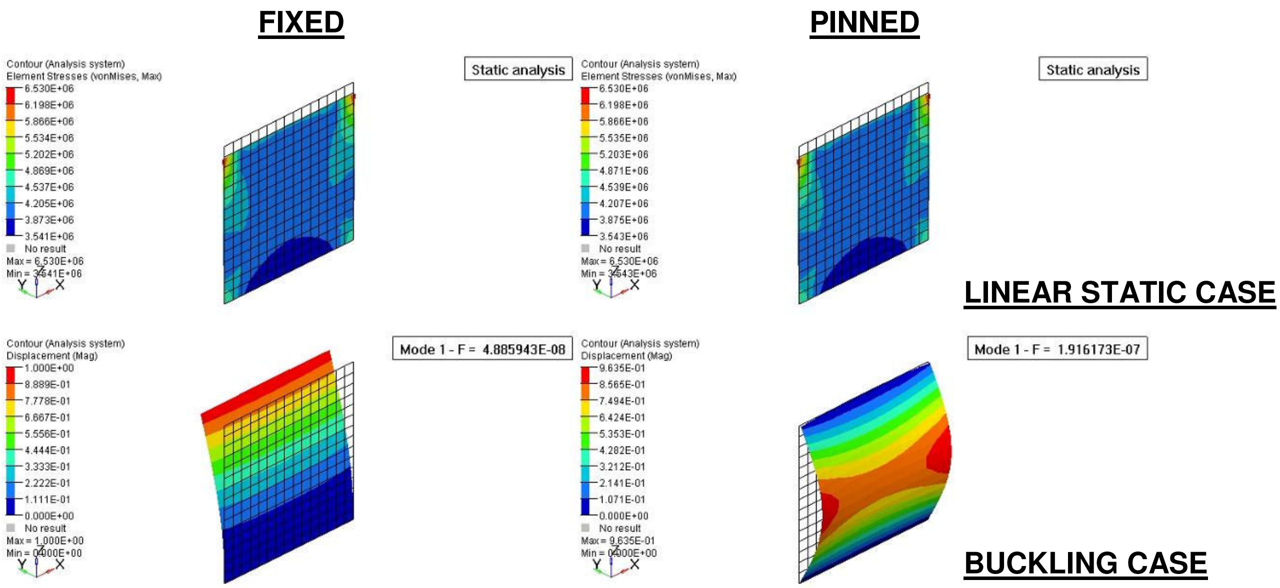


Figure 29 | Aspect Ratio 1:1 for line extrusion

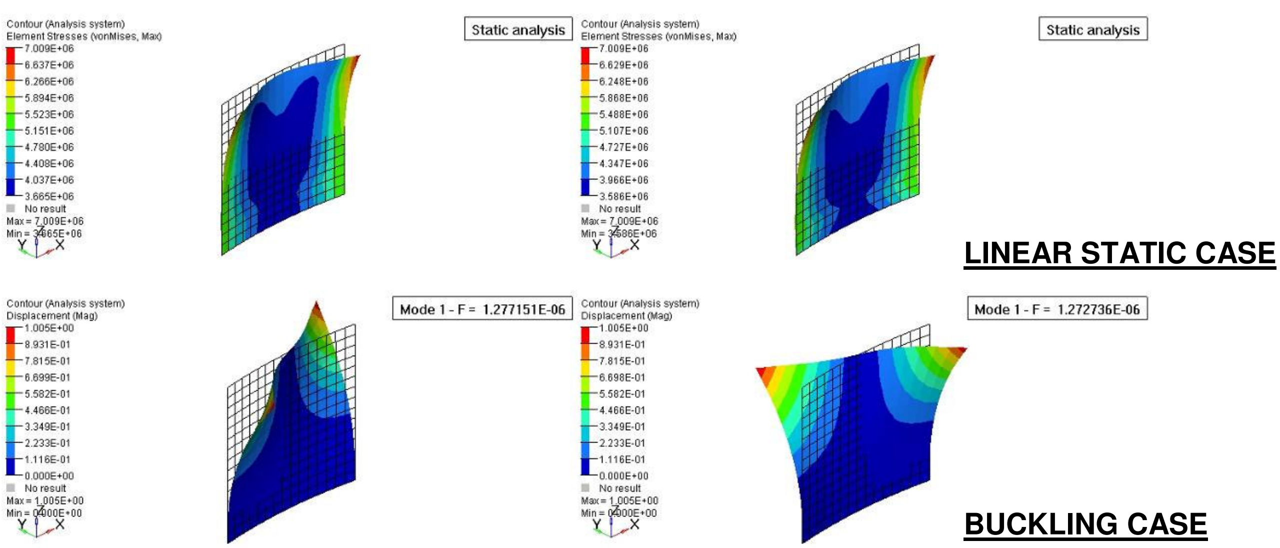


Figure 30 | Aspect Ratio 1:1 for shallow curve extrusion

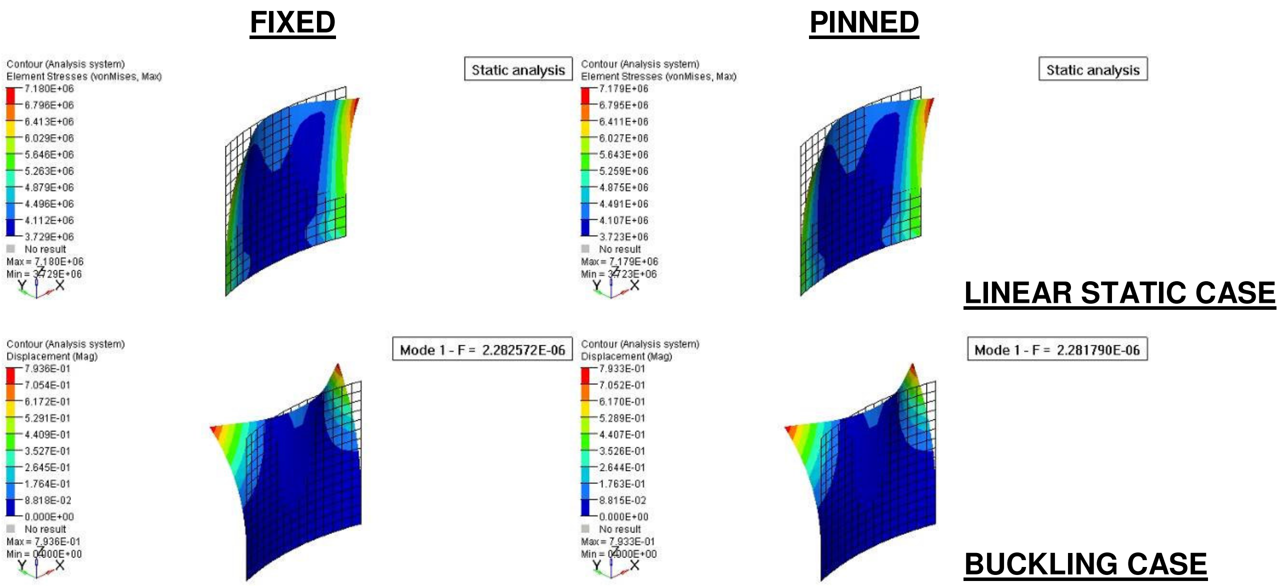


Figure 31 | Aspect Ratio 1:1 for deep curve extrusion

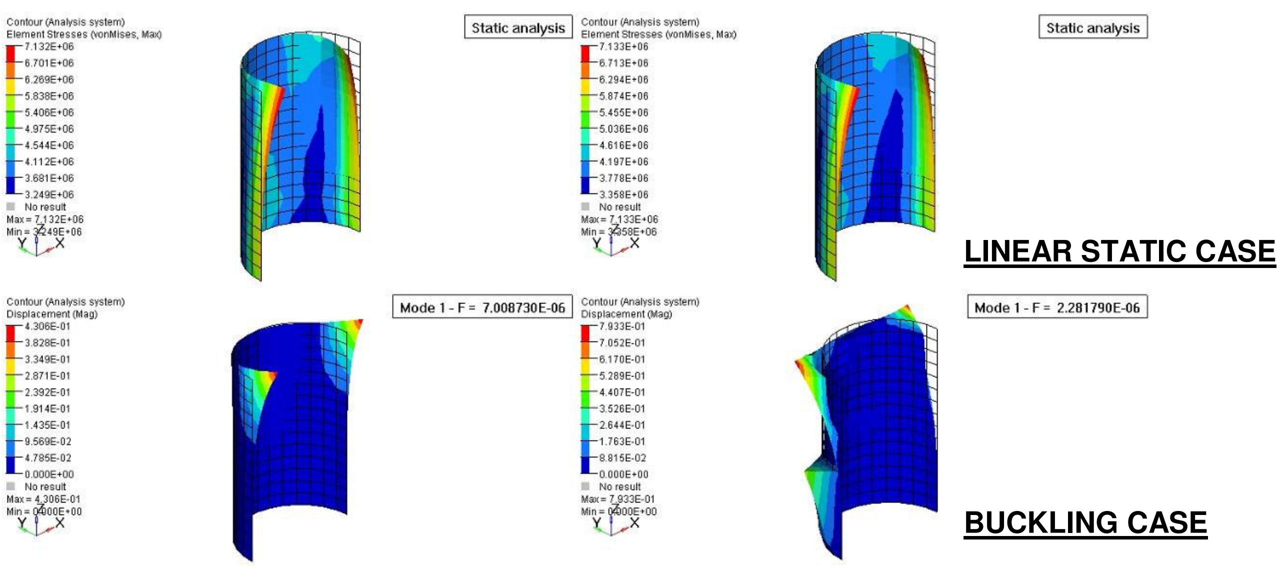


Figure 32 | Aspect Ratio 1:1 for semi-circle extrusion

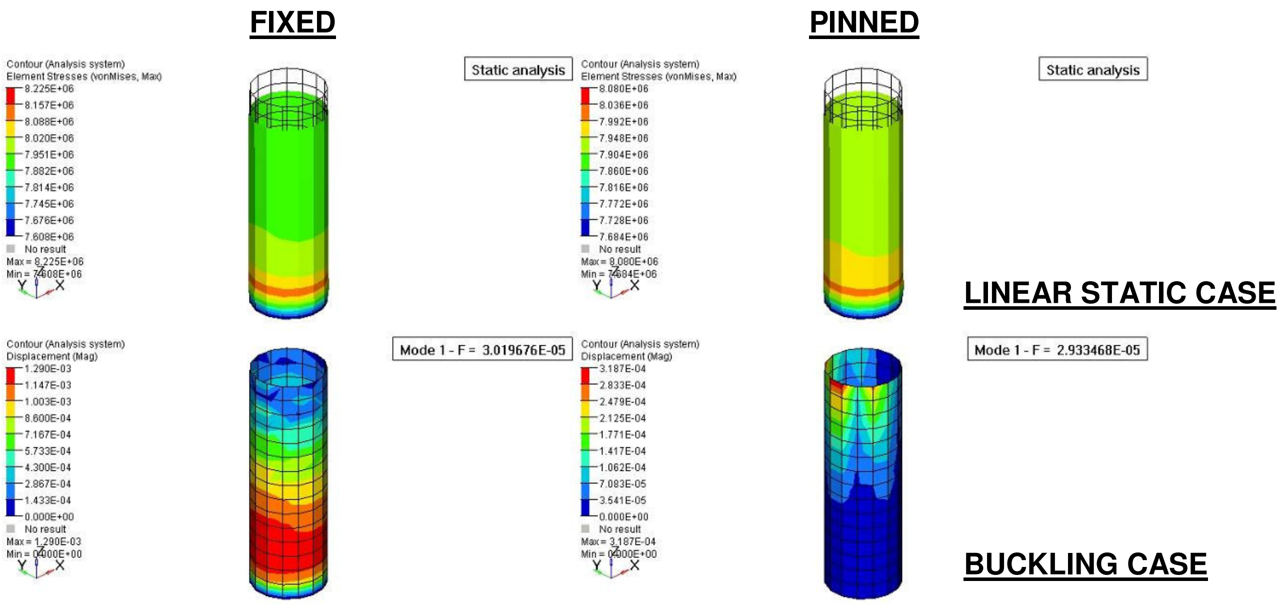


Figure 33 | Aspect Ratio 1:1 for circle extrusion

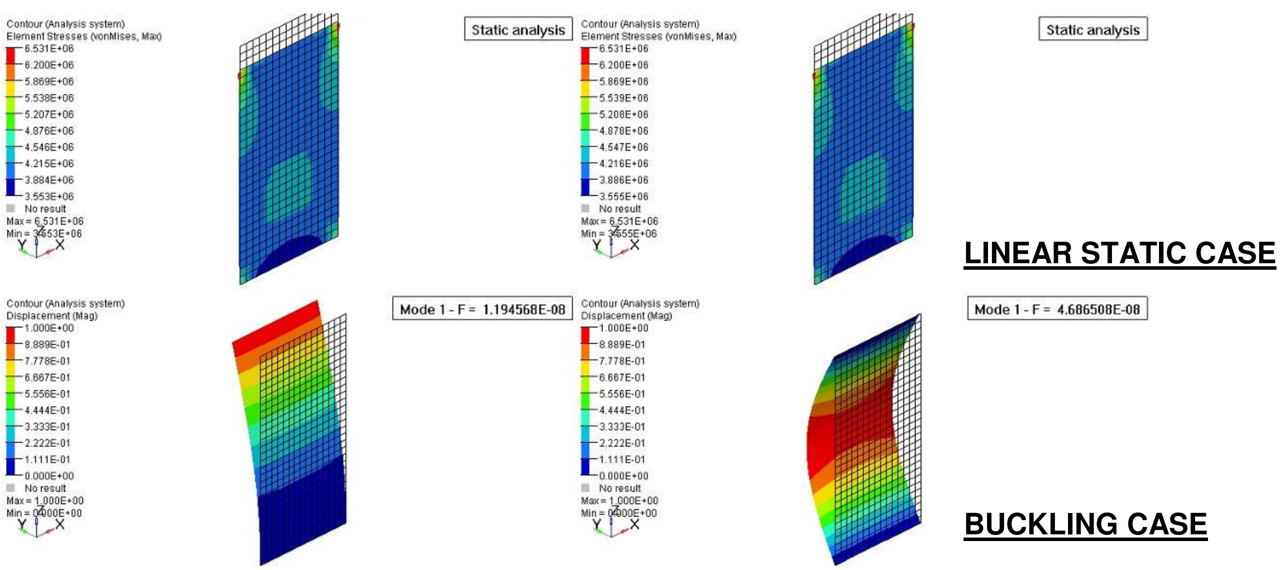


Figure 34 | Aspect Ratio 1:2 for line extrusion

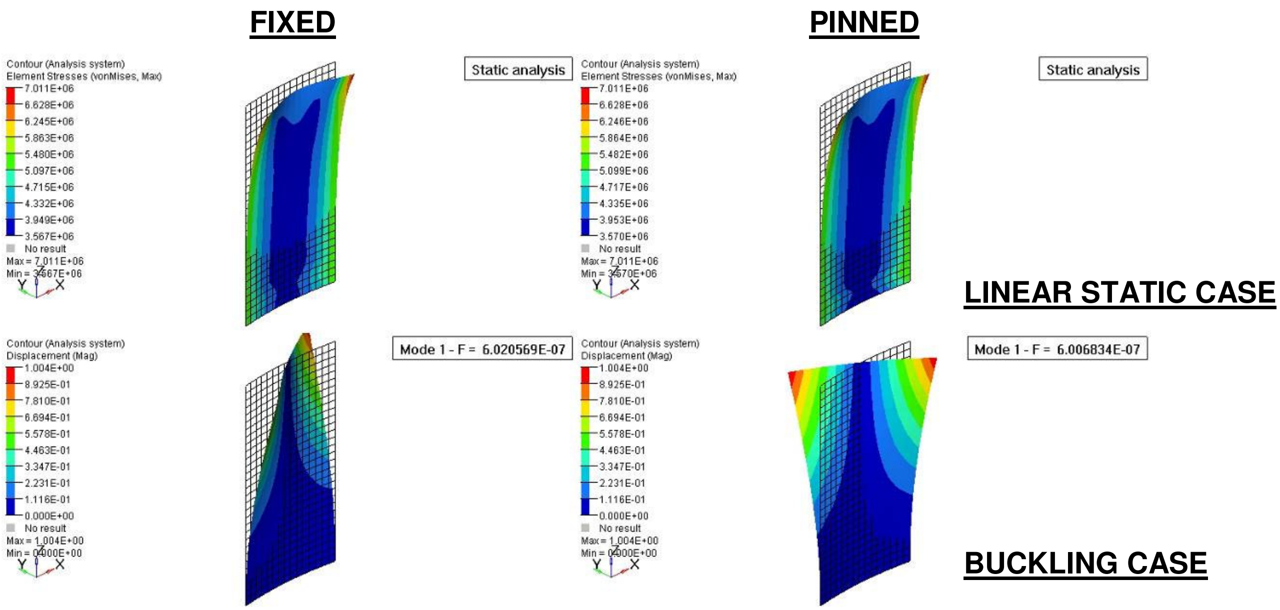


Figure 35 | Aspect Ratio 1:2 for shallow curve extrusion

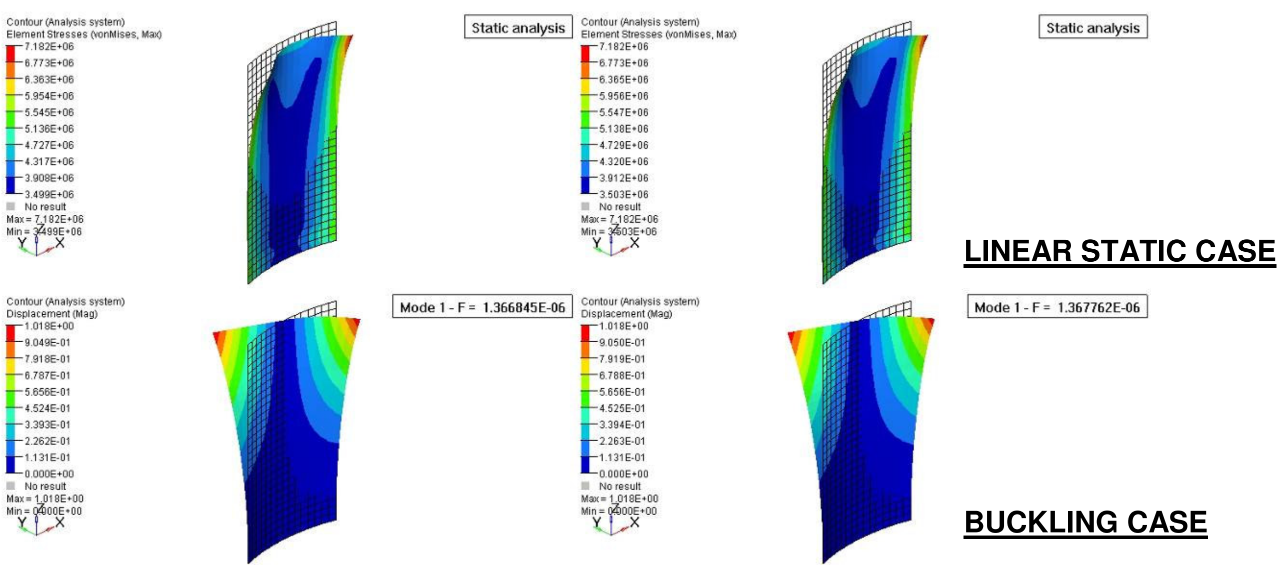


Figure 36 | Aspect Ratio 1:2 for deep curve extrusion

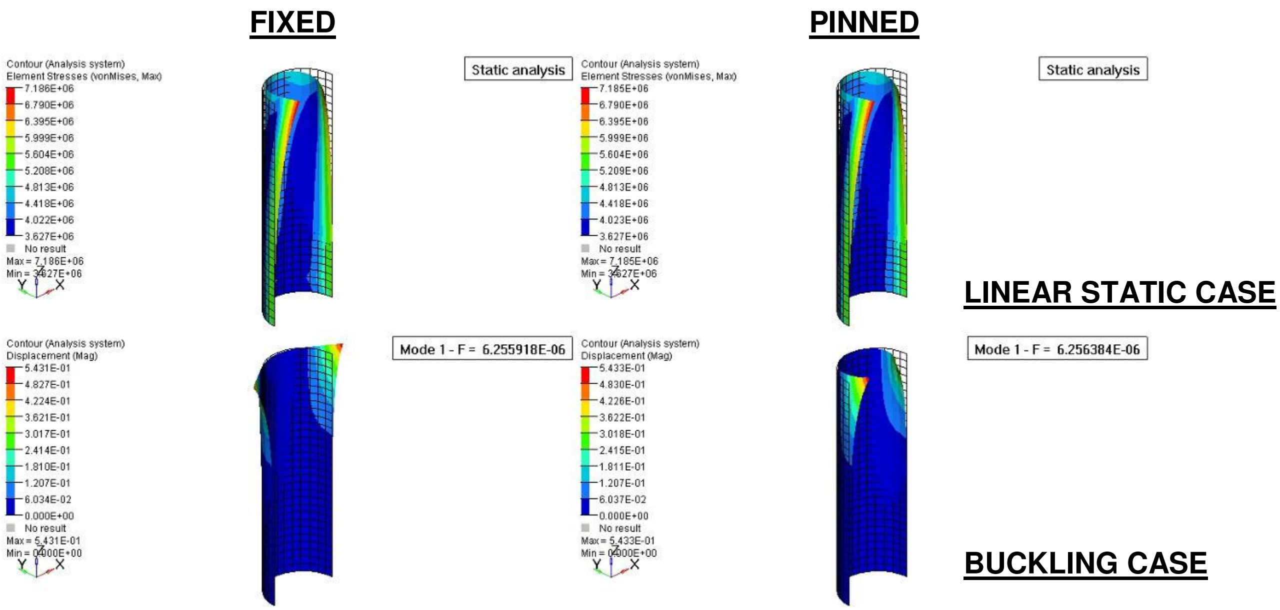


Figure 37 | Aspect Ratio 1:2 for semi-circle extrusion

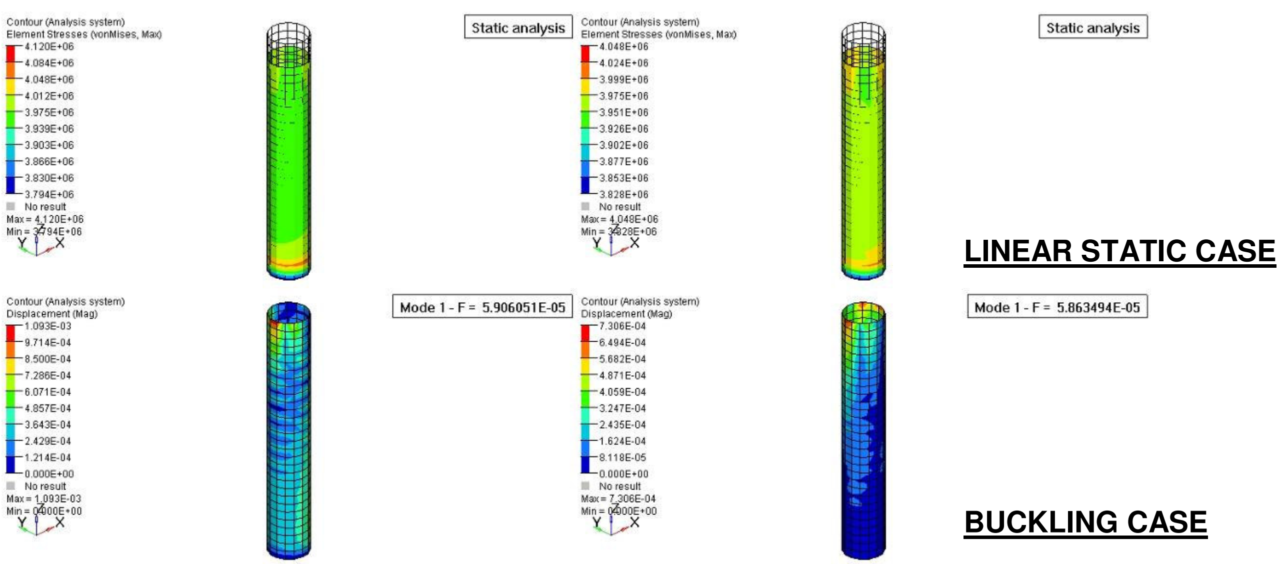


Figure 38 | Aspect Ratio 1:2 for circle extrusion

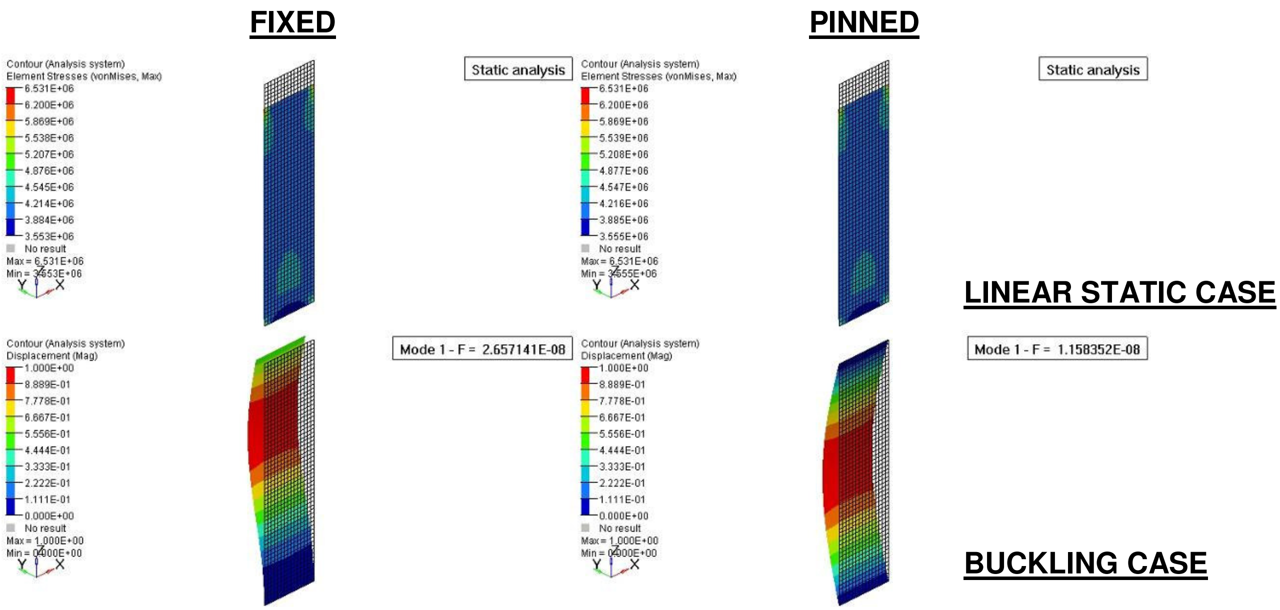


Figure 39 | Aspect Ratio 1:4 for line extrusion

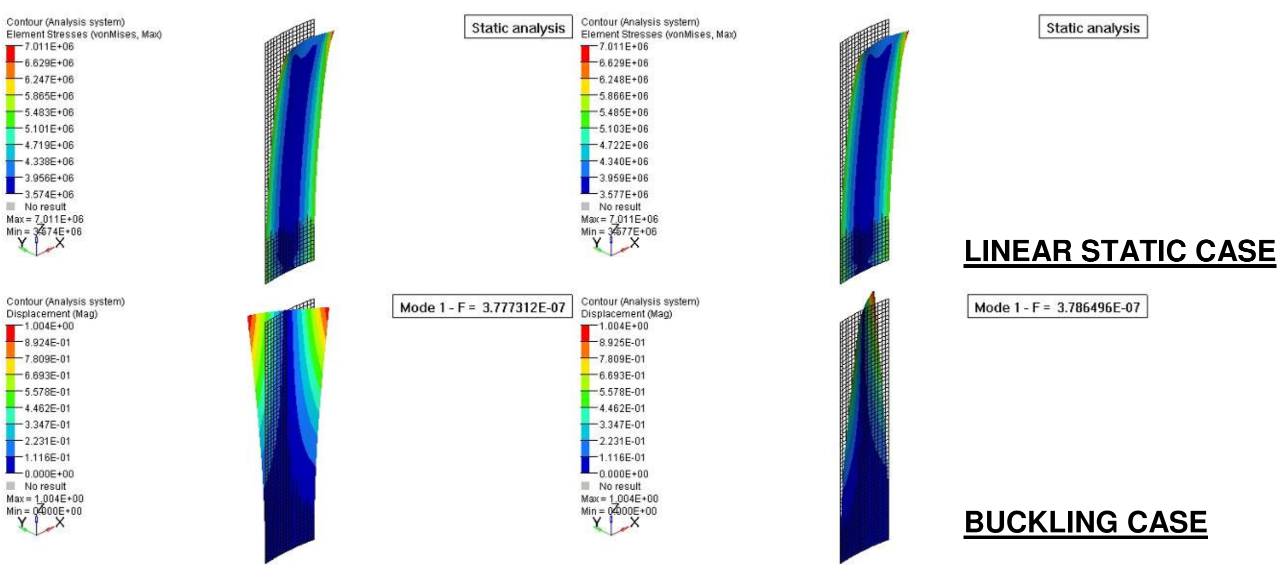


Figure 40 | Aspect Ratio 1:4 for shallow curve extrusion

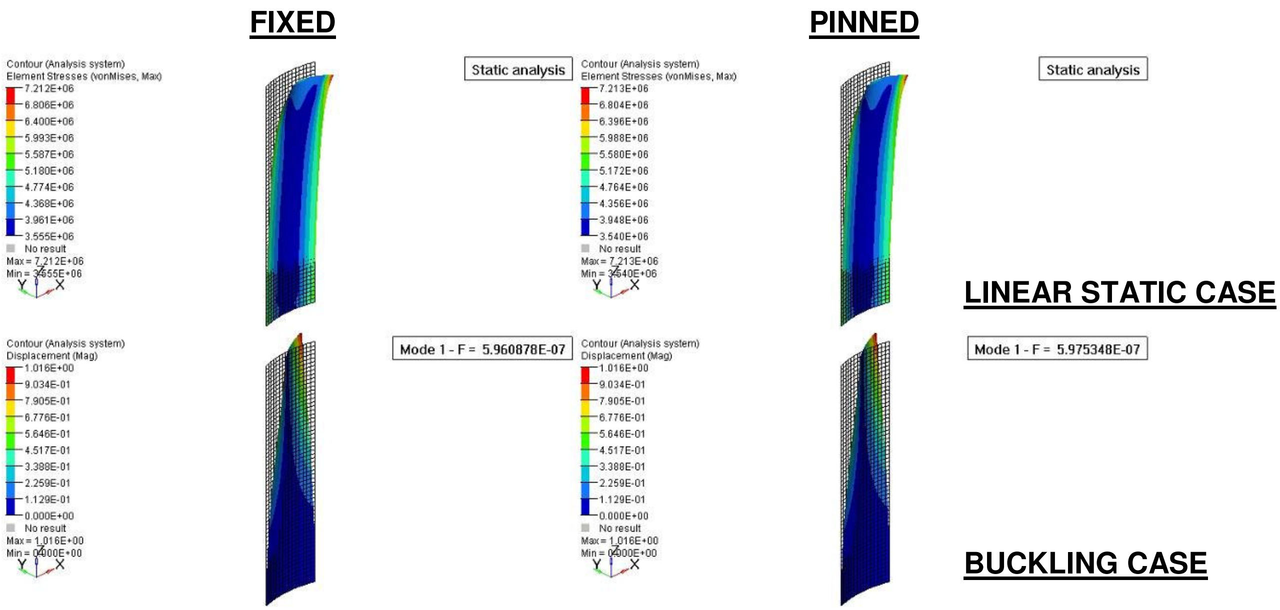


Figure 41 | Aspect Ratio 1:4 for deep curve extrusion

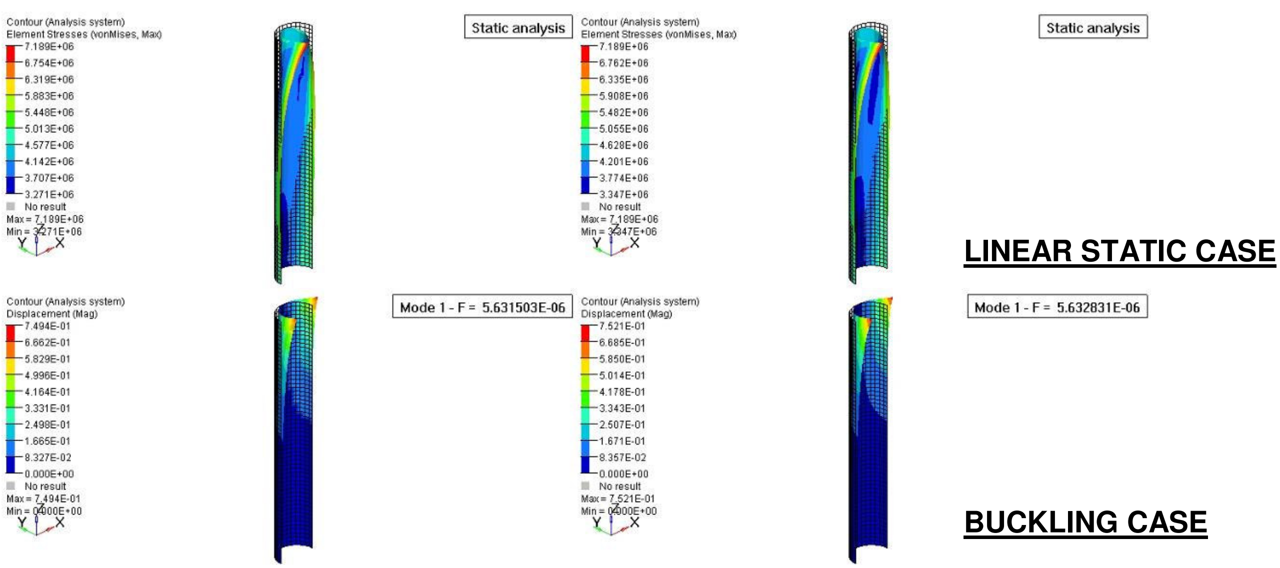


Figure 42 | Aspect Ratio 1:4 for semi-circle extrusion

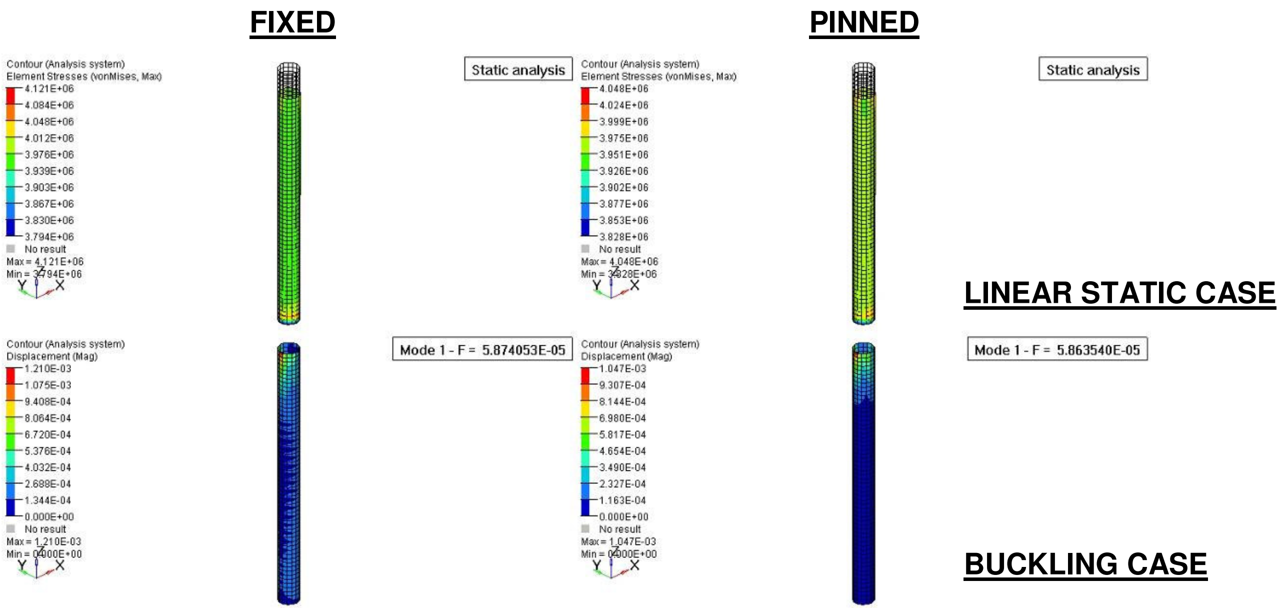


Figure 43 | Aspect Ratio 1:4 for circle extrusion

The results of this test show that shape instability and in-plane buckling for a single curvature surface are quite unpredictable and rather severe. Once shape closure is achieved, which is the case of the cylinder, the system gains significant stability, but as can be observed in the color plot unpredictable and asymmetrical stresses are still produced.

CHAPTER 9 | EXERCISE 2:

DOUBLE CURVATURE PLATE WITH APPLIED PERPENDICULAR FORCES

The second exercise tests the behavior of a circular plate as double curvature shape is applied with a force acting perpendicular, or normal, to the plate. Each model was analyzed for buckling modes, Von Mises stresses, and displacement and is shown as a colored contour plot with deformed geometry over the original undeformed shape shown as a wireframe. The deformed geometry has been exaggerated to emphasize the formal behavior.

The formal operation here can be understood as a bulge, or 3D stretching. By giving shape in multidirections and with double curvature one expects to achieve a more robust and stable shape where forces are allowed to move through the surface by taking various load paths. Buckling behavior is not intuitively predictable. It is unknown whether the shapes will have stable post-buckling curves or unstable post-buckling curves. The model is again a thin walled shell with material properties analogous to steel. The units from Table 2 were used for this exercise. Buckling factors [Eigenvalues] should be multiplied by 10^{-6} for the proper Eigenvalue.

Figure 44 | Dome shape and loading scheme

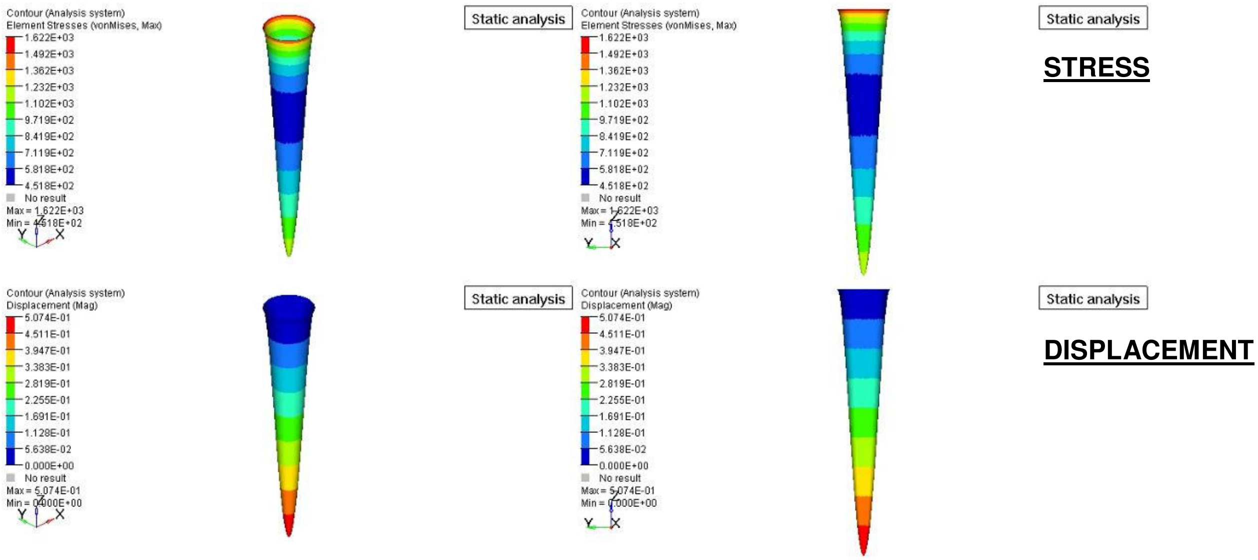


Figure 45 | Flat plate

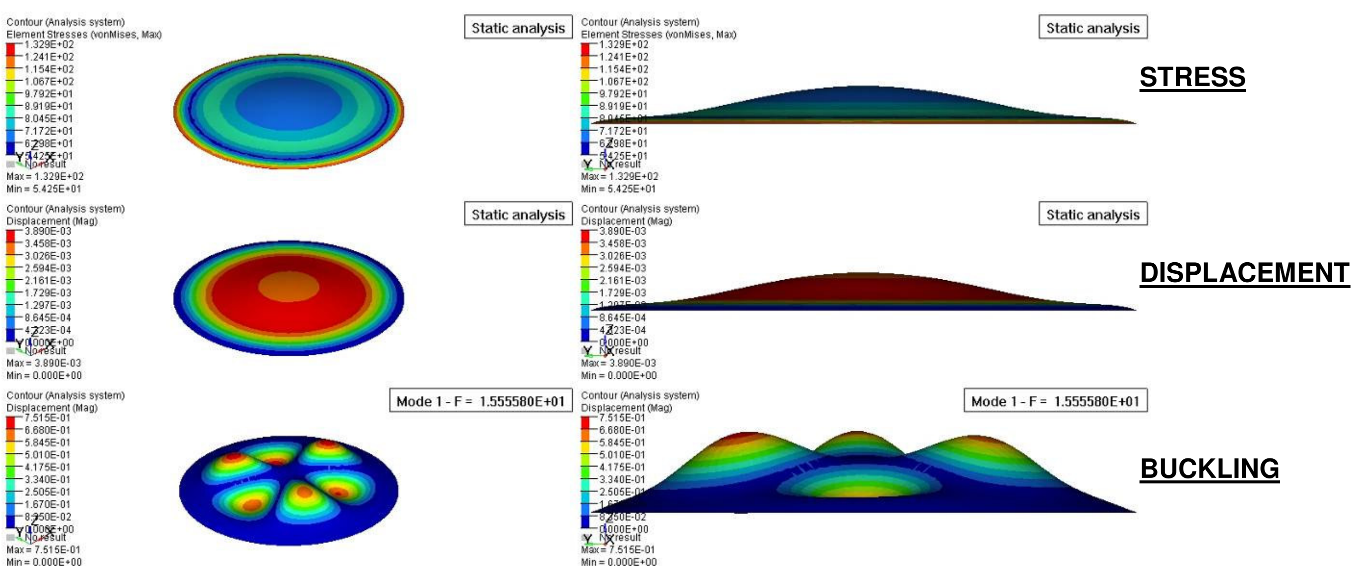


Figure 46 | Dome 1

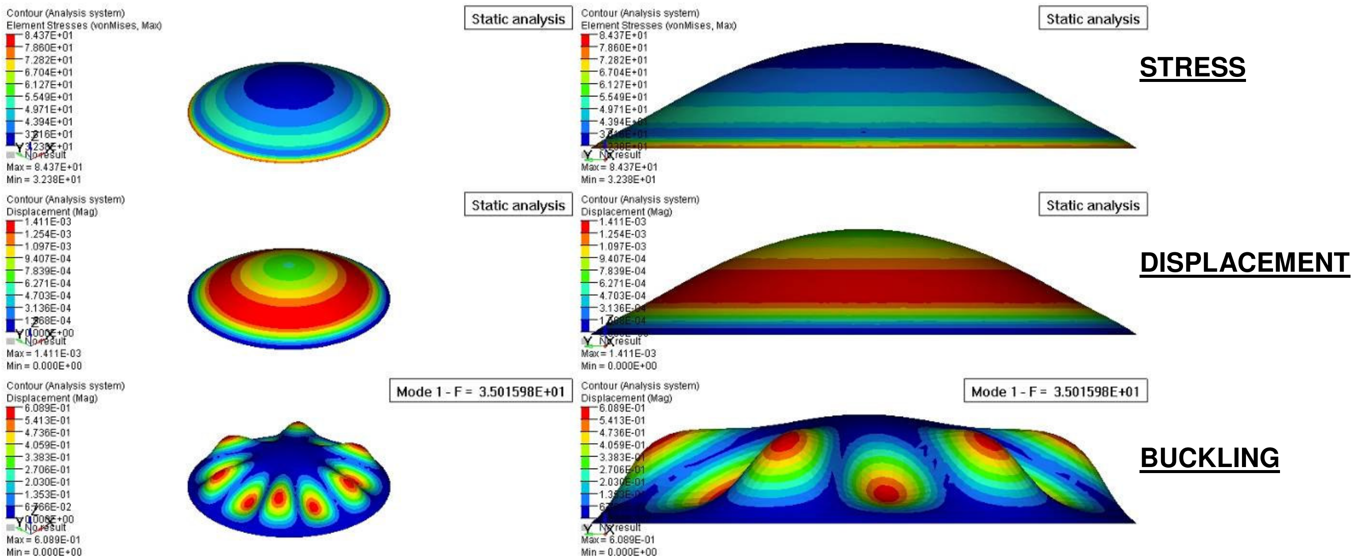


Figure 47 | Dome 2

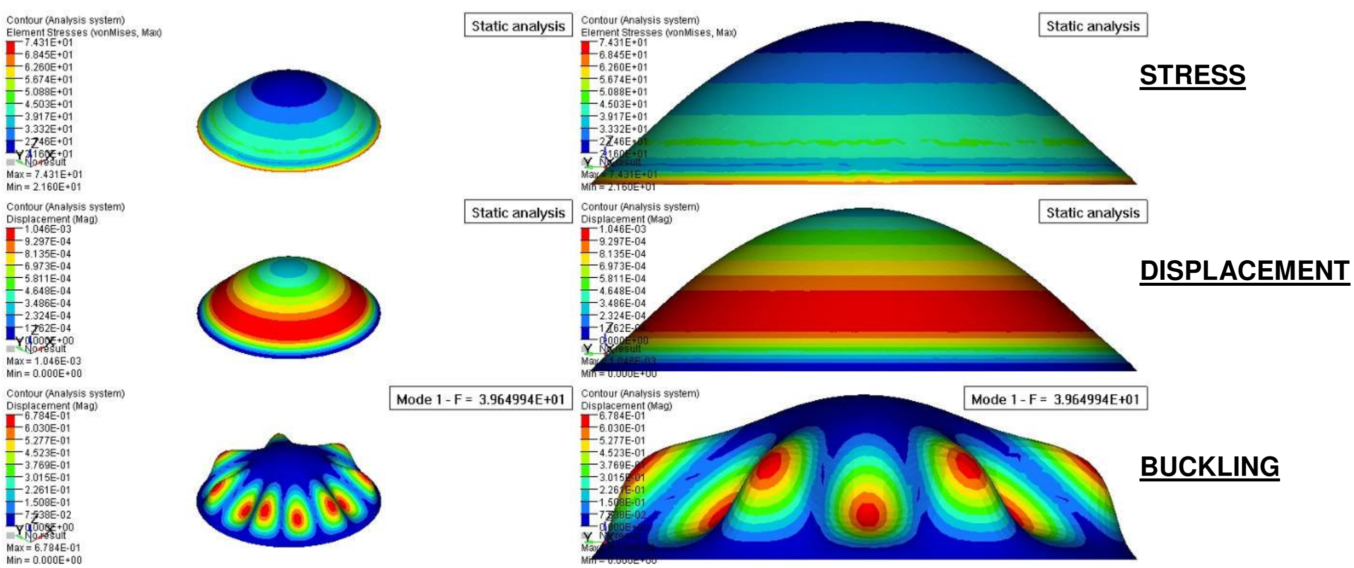


Figure 48 | Dome 3

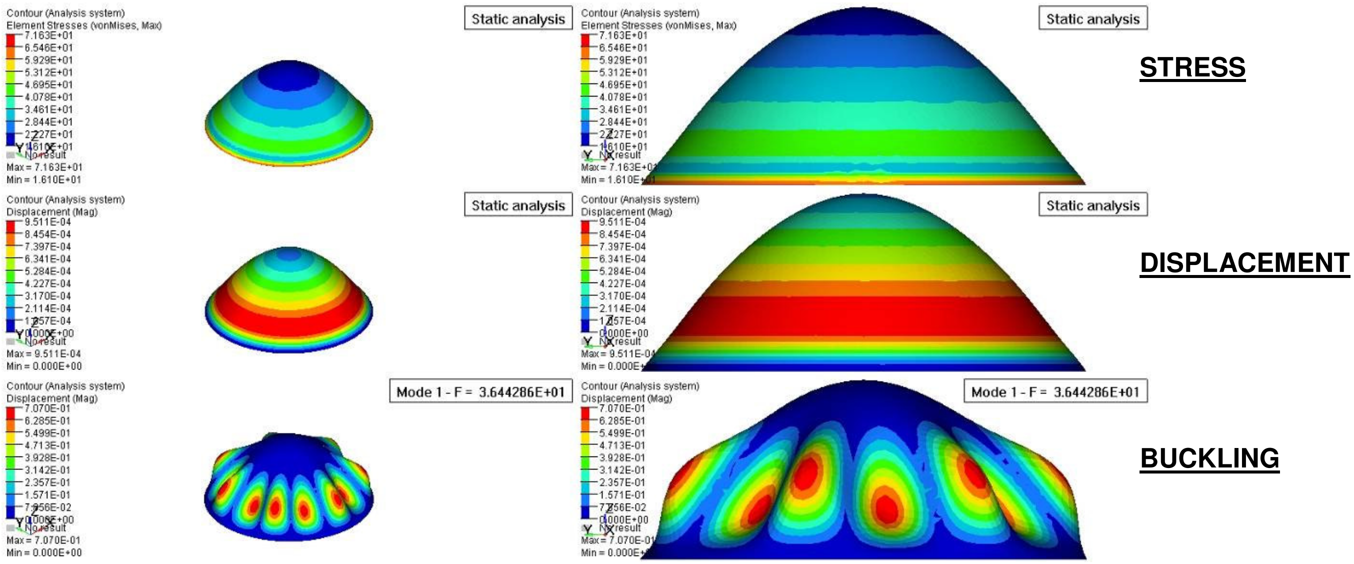


Figure 49 | Dome 4

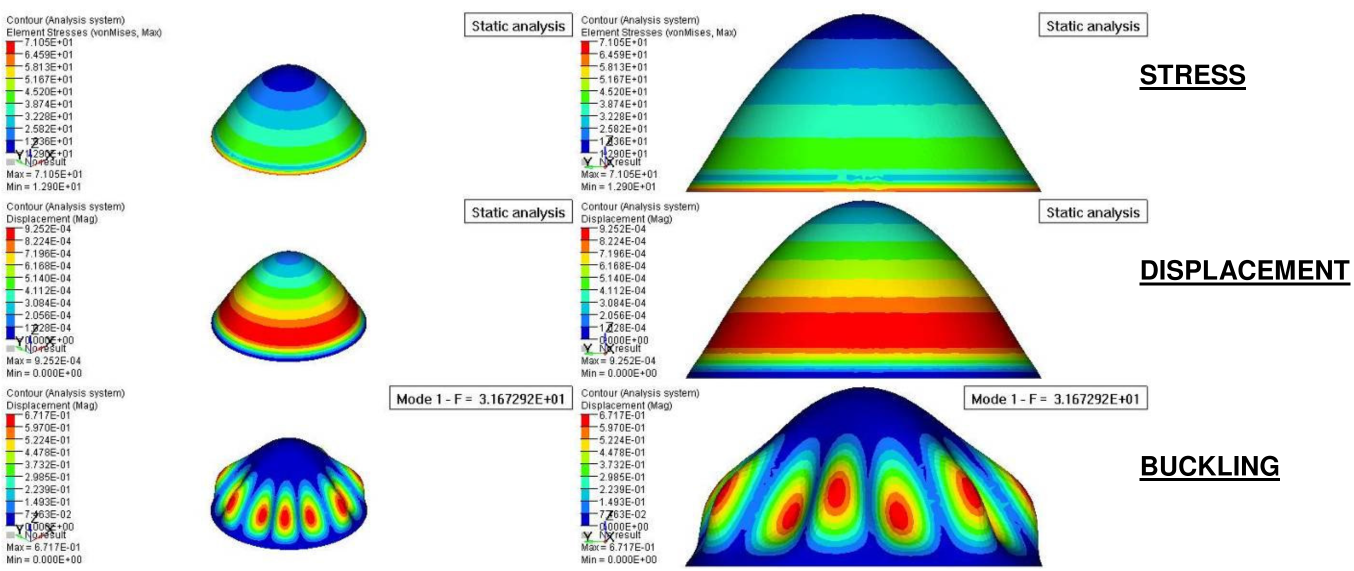
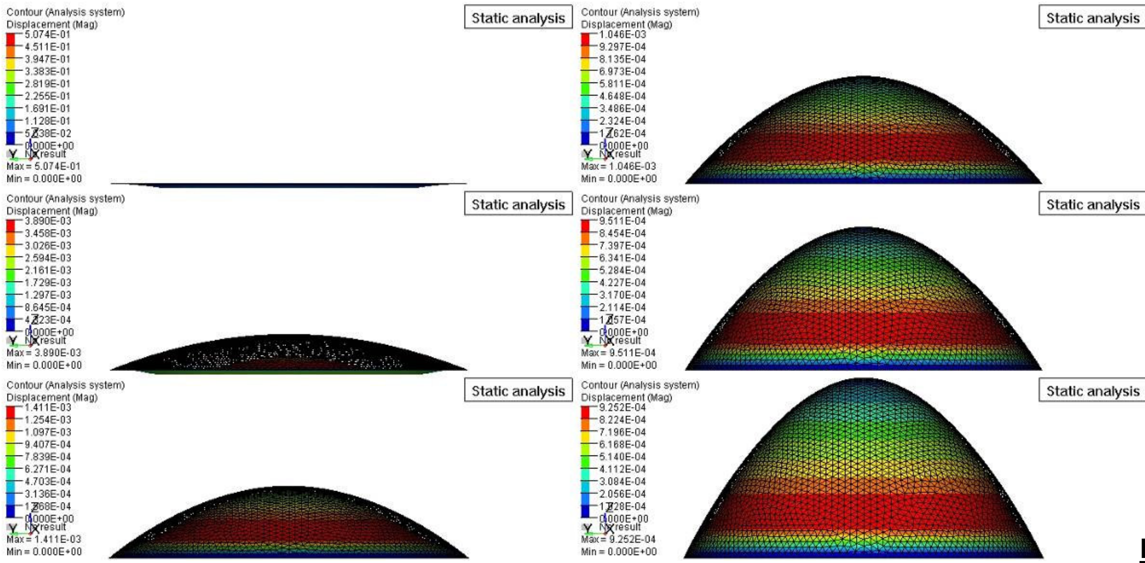
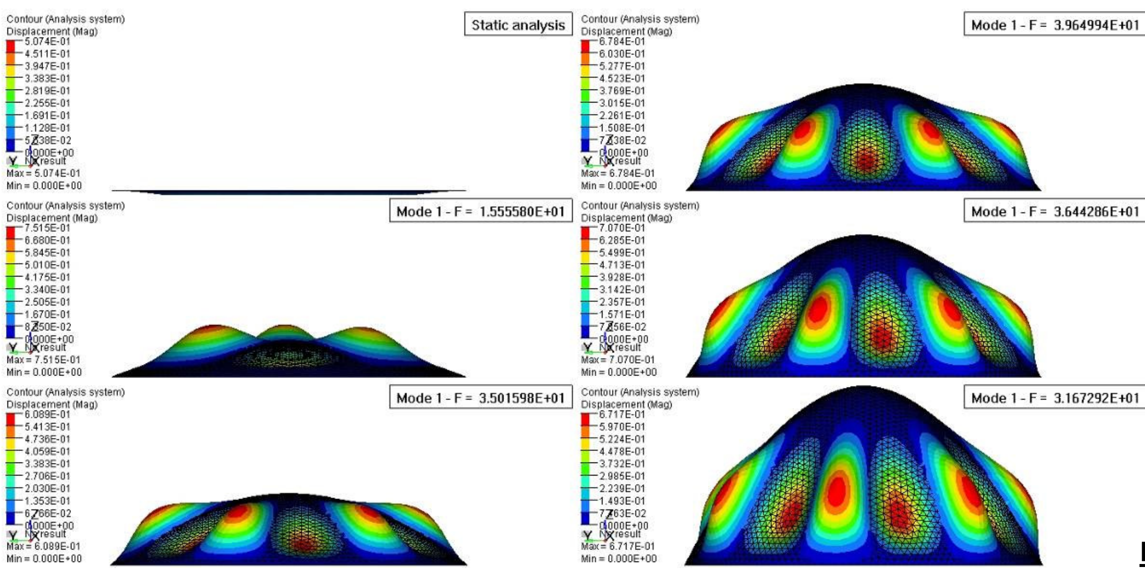


Figure 50 | Dome 5



DISPLACEMENT

Figure 51 | Comparison of displacement for all shapes



BUCKLING

Figure 52 | Comparison of buckling behavior for all shapes

The analysis clearly shows the stiffness derivated by the dome shape relative to the flat plate. Even slight curvature in the plate produces dramatic resistance to the applied loads. As the amount of curvature increases the amount of deformation decreases as can be seen with the deformed surface superimposed on the undeformed wireframe. Clearly the flat plate is nearly worthless in this loading case [an analysis of tensile strength would be quite different however]. The exaggerated displacements show that the flat plate will deform severely. Additionally, since this plate only has tensile stresses a buckling mode analysis cannot be performed as buckling is only a phenomena of compressive action. These dome shapes are now assumed to have stable post-buckling curves as buckling behavior has not created large global deformations, however, more analysis is necessary to definitively confirm this.

CHAPTER 10 | DESIGN EXERCISE: 'FOLDING THE DOME'

The following design experiment tests the premise of using FEA as structural feedback in the iterative design of a self-supporting structural skin. Starting with a semi-spherical dome, the experiment is set up as a prototypical transformation of an archetypical form. The original dome has a span of 43 meters, as taken from the dimensions of the Pantheon in Rome, and is set on top of four pendentive arches. The thickness of the surface is 0.00635 meters and is modeled with the properties of mild steel. After the CAD model was converted to a FE mesh, the FE model was loaded with a uniform load of 5.3×10^6 newtons, which is the equivalent to the load that would be produced by taking the area of the structure's footprint and loading it with a generically derived load of 60 pounds per square foot [see Chapter 7 for loading logic]. The base of the four pendentives were then continuously fixed at every FE node and given zero DOF. An analysis was then run on the dome for buckling, stress, and displacement. The results of this analysis were captured, considered, and then used in the transformation of the dome. Each transformational iteration tries to introduce shape stiffening operations in areas of high deformation. Geometric complexity and surface continuity are gradually produced as overall stiffness is increased.

Decision making for which formal operations would be used came from a mixture of designer's intensions/intuitions, analytical results from the FE dome model, and knowledge of particular shape behaviors as discovered in Exercises 1 and 2.

The process of translation from CAD to pre-processor to post-processor and back to CAD is illustrated as a series of screen captures in figures 58-67. Units from Table 1 were used for all FE models.

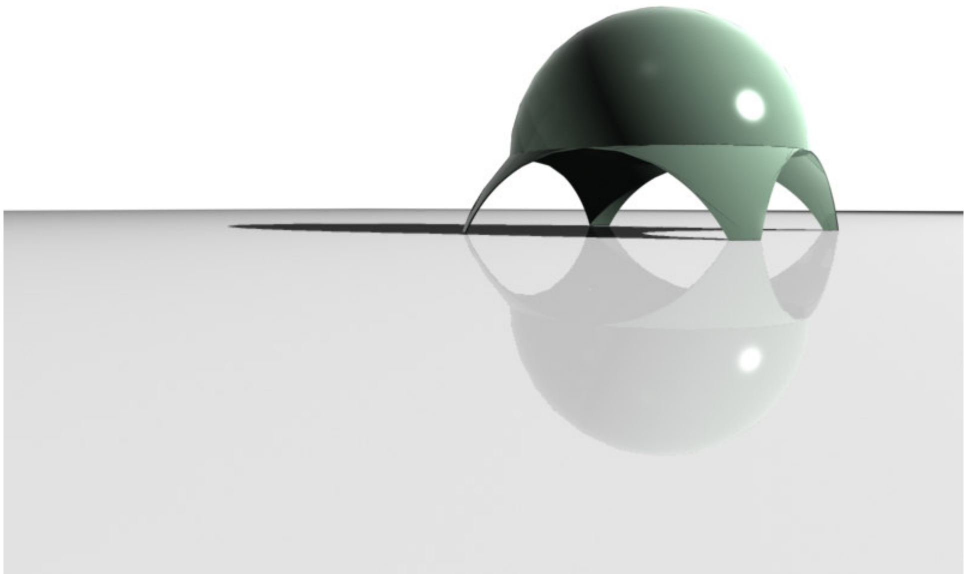


Figure 53 | Perspective of initial dome form

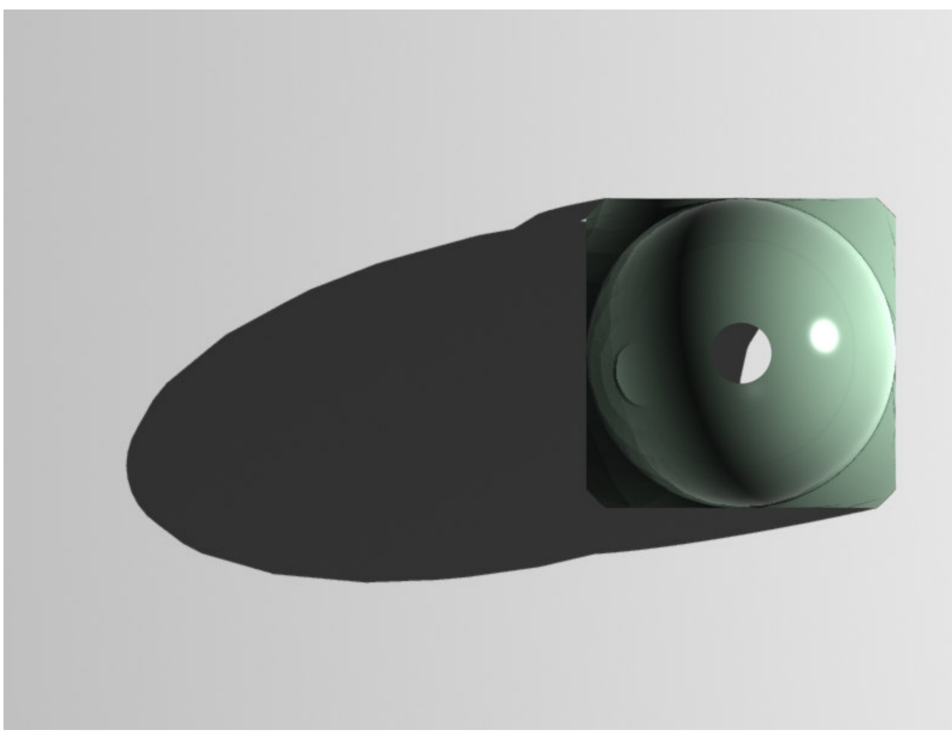


Figure 54 | Plan view of initial dome form

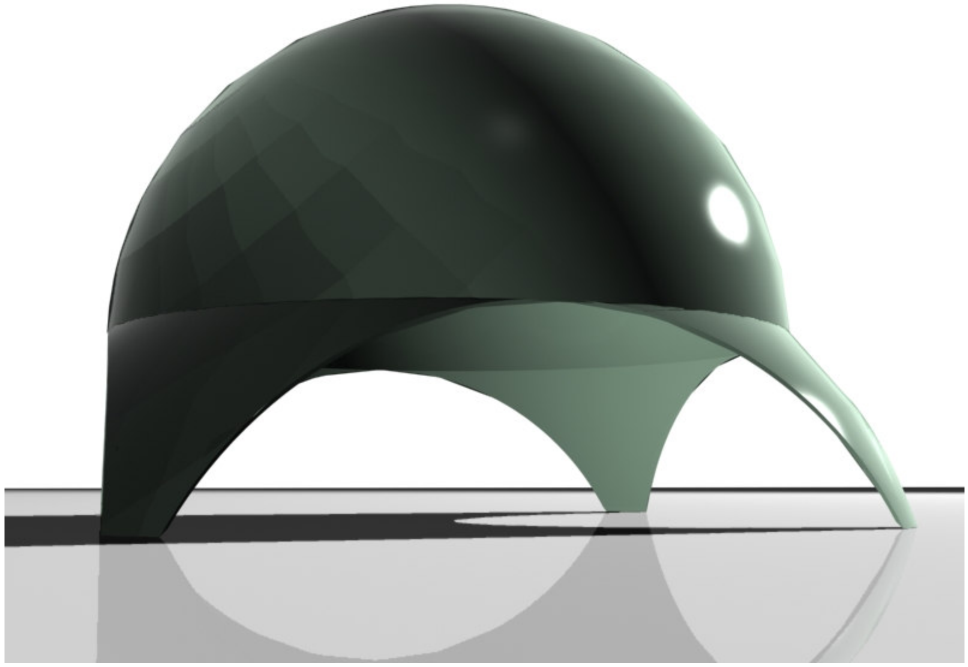


Figure 55 | Perspective of initial dome form

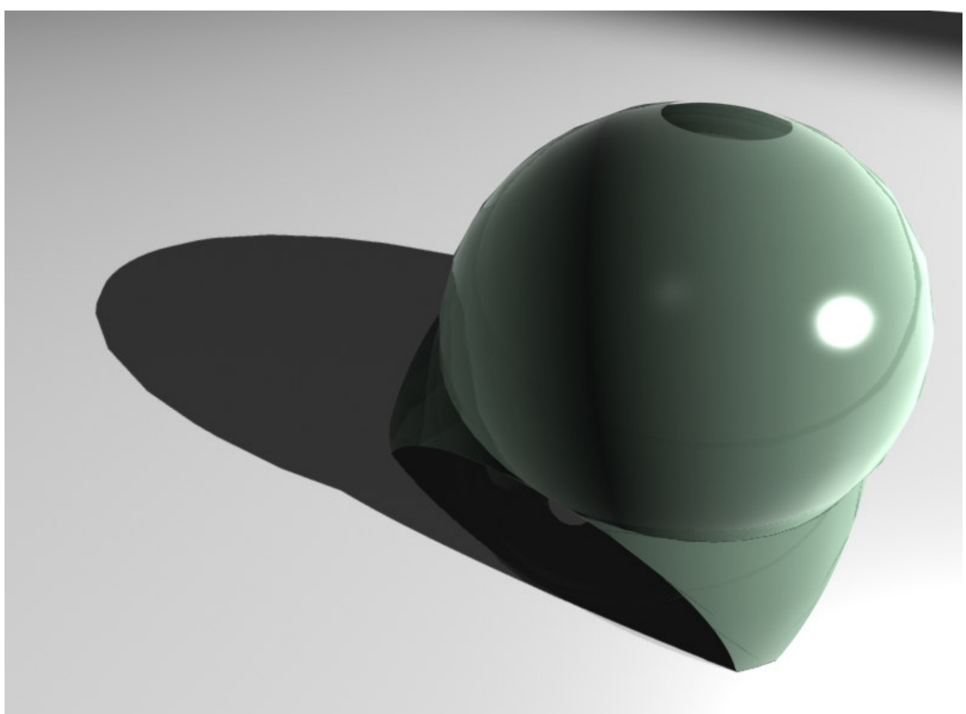


Figure 56 | Birdseye view of initial dome form

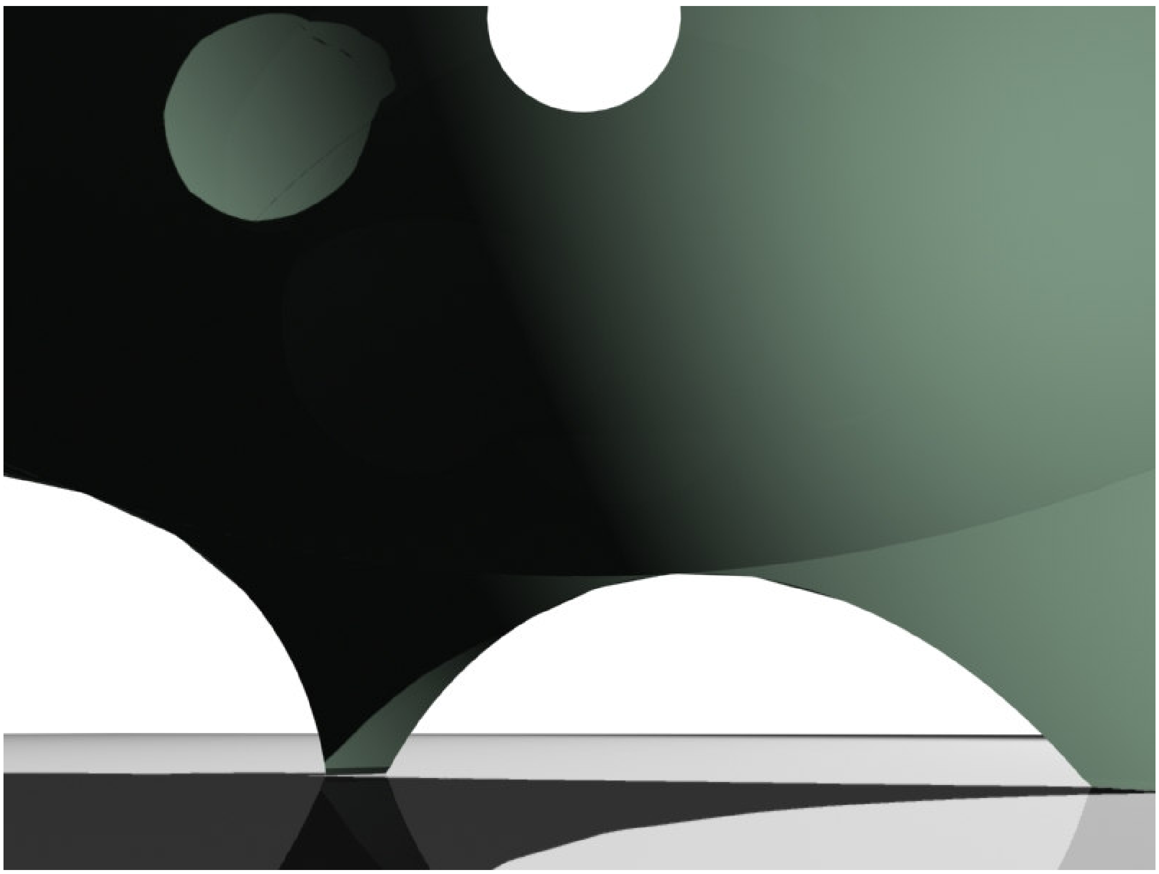


Figure 57 | Interior view of initial dome form

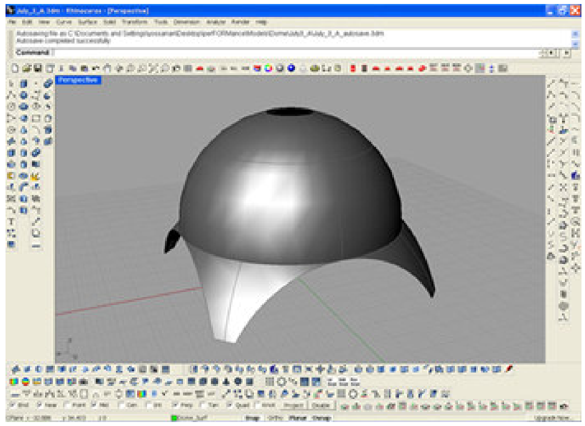


Figure 58 | Initial Geometry in CAD

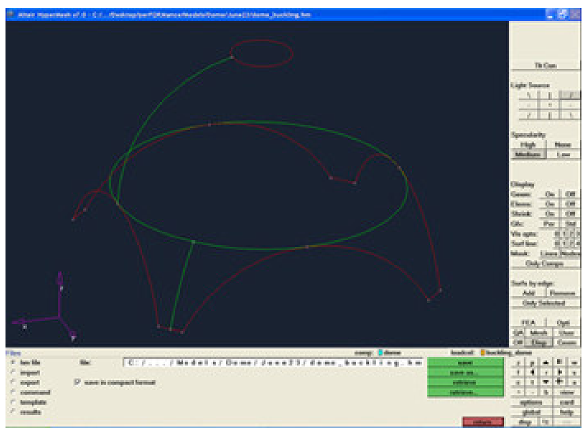


Figure 59 | IGES file imported to pre-processor

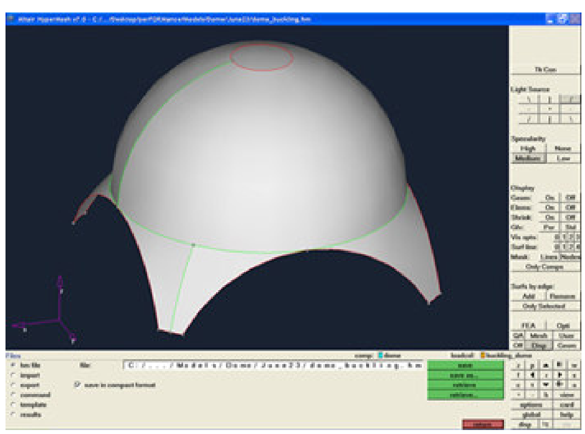


Figure 60 | Geometric representation in pre-processor

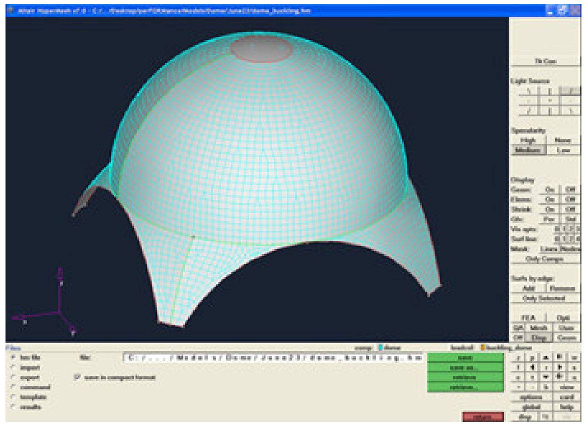


Figure 61 | Superimposition of geometry and mesh in pre-processor

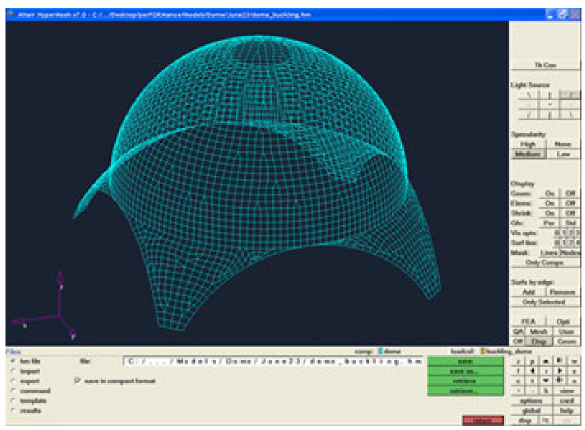


Figure 62 | Mesh representation in pre-processor

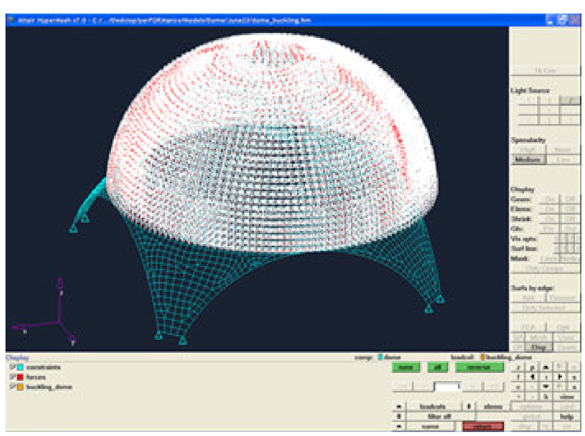


Figure 63 | Mesh with boundary conditions in pre-processor

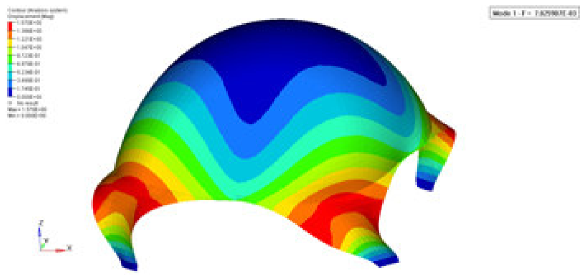


Figure 64 | Analytical results and deformed shape in post-processor

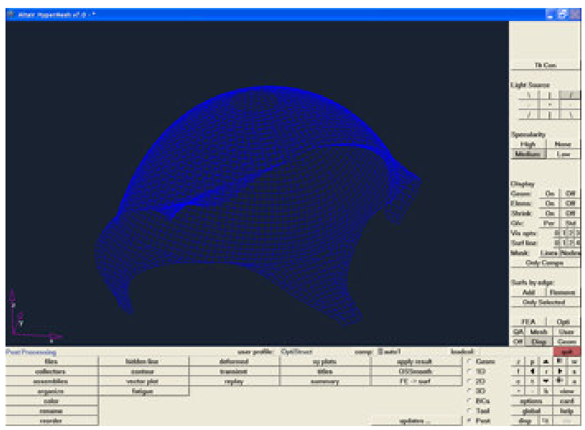


Figure 65 | Deformed mesh imported into pre-processor from post-processor

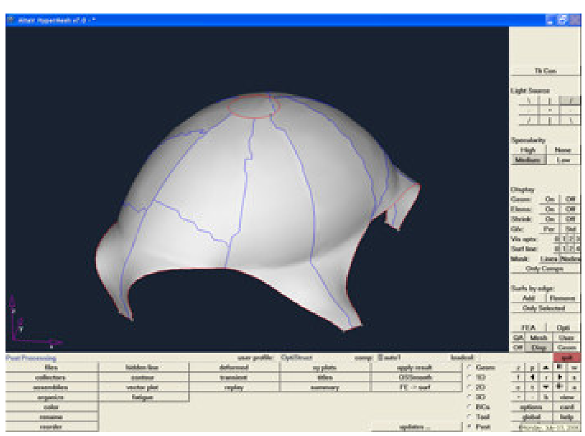


Figure 66 | Geometric surface extracted from mesh in pre-processor

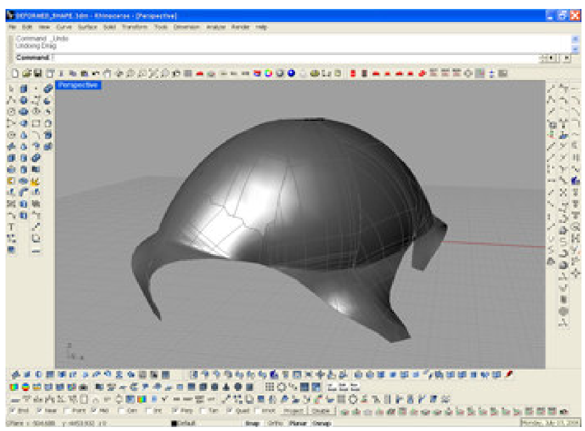


Figure 67 | Geometric surface imported into CAD from pre-processor

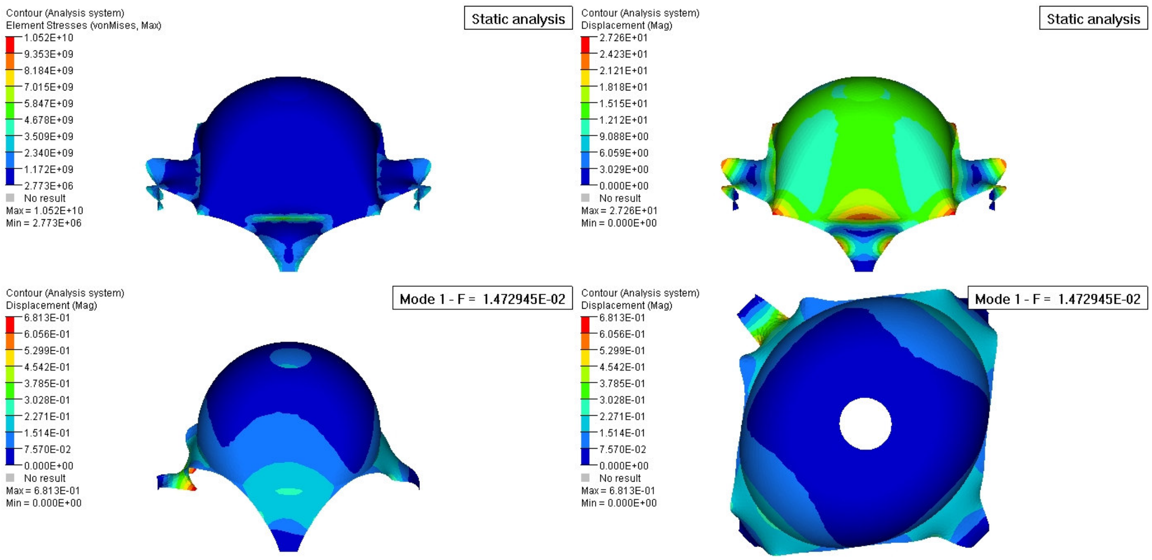


Figure 68 | Analytical results showing stresses, displacements, and buckling

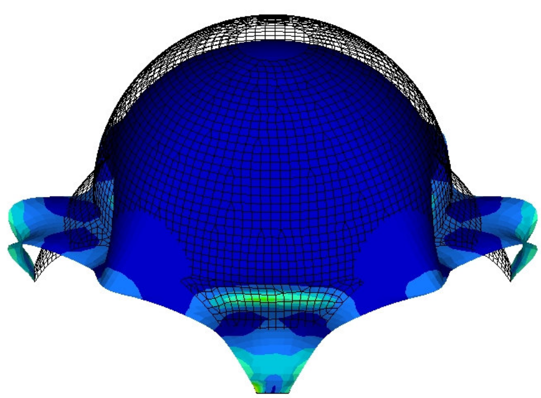


Figure 69 | Analytical results showing stress contours superimposed on undeformed shape

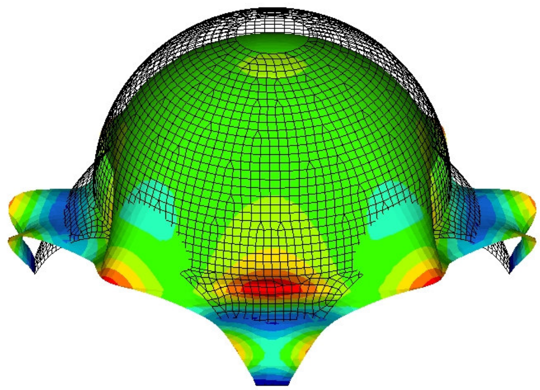


Figure 70 | Analytical results showing displacement contours superimposed on undeformed shape

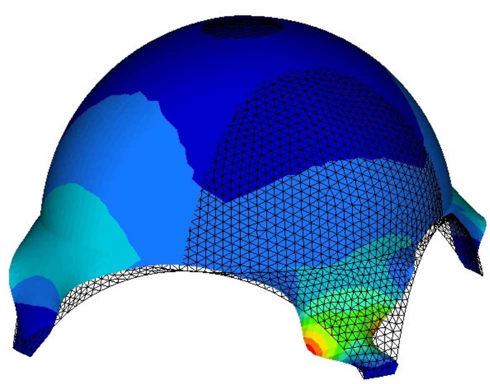


Figure 71 | Analytical results showing buckling mode superimposed on undeformed shape

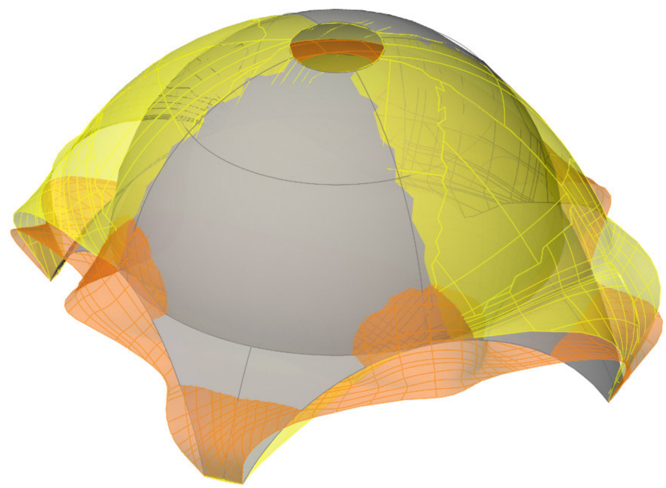


Figure 72 | Birdseye of superimposed forms - original dome [gray], buckling mode [yellow], and displacement [orange]

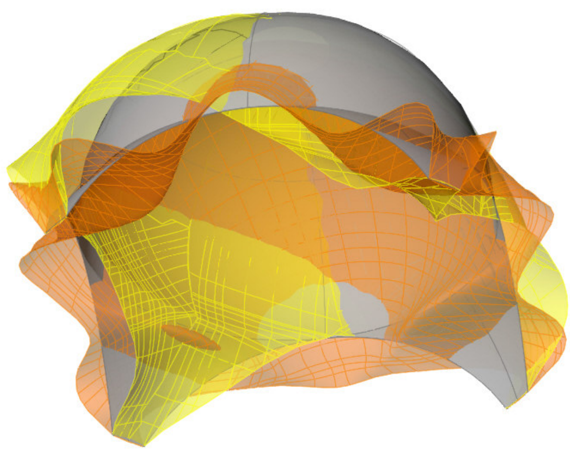


Figure 73 | Worms eye of superimposed forms - original dome [gray], buckling mode [yellow], and displacement [orange]

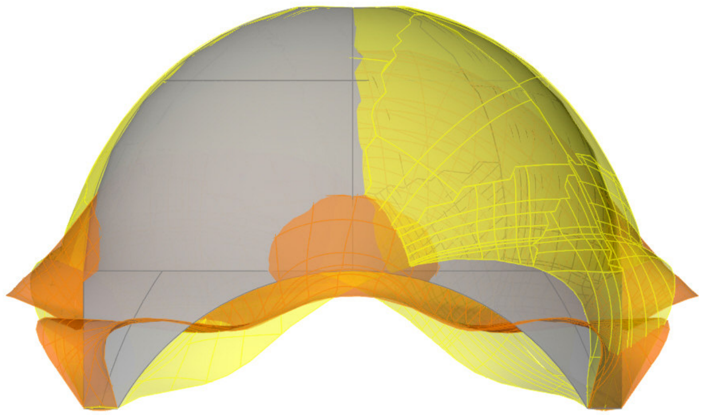


Figure 74 | Elevation of superimposed forms - original dome [gray], buckling mode [yellow], and displacement [orange]

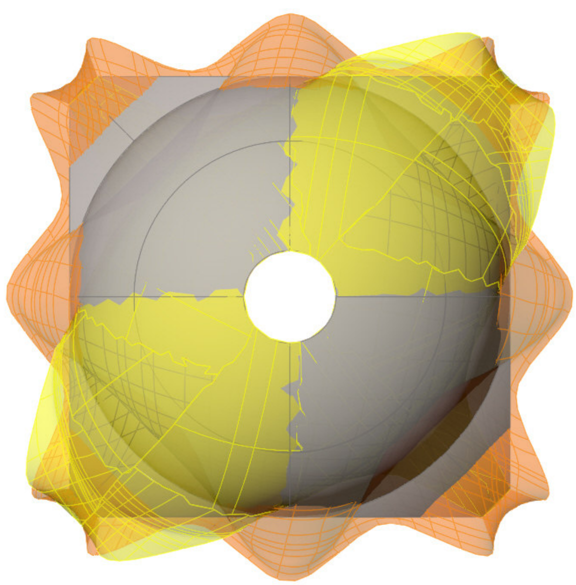


Figure 75 | Plan of superimposed forms - original dome [gray], buckling mode [yellow], and displacement [orange]

Analysis of the original geometry shows buckling behavior in the pendentive legs that identified an opportunity for shape stiffening operations. Additionally, the upper portion of the dome was shown to be performing quite well with the original geometry. Therefore a strategy of lofting from deep curves in the lower regions to shallow curves in the upper region was implemented. The original geometry was first superimposed with the deformed geometries from both the buckling and displacement analyses to give a spatial frame of reference to the designer. This is of course an exaggerated representation, however it is an intuitive context for spatial thinkers. The shapes were then deconstructed and used to generate deep sinuous curves which were then lofted to produce the four folded legs in the next iteration. The curves were drawn perpendicular to the line of intersection produced by slicing a plane through the dome on a 45-degree diagonal in plan. In other words, deep curves were drawn perpendicular to the original dome and then swept, using lofts, 1-rail sweeps, 2-rail sweeps, and surface blends. The material thickness remained constant throughout all iterations, more or less maintaining an equivalent usage of material.

Figure 76 | Perspective of first iteration dome transformation

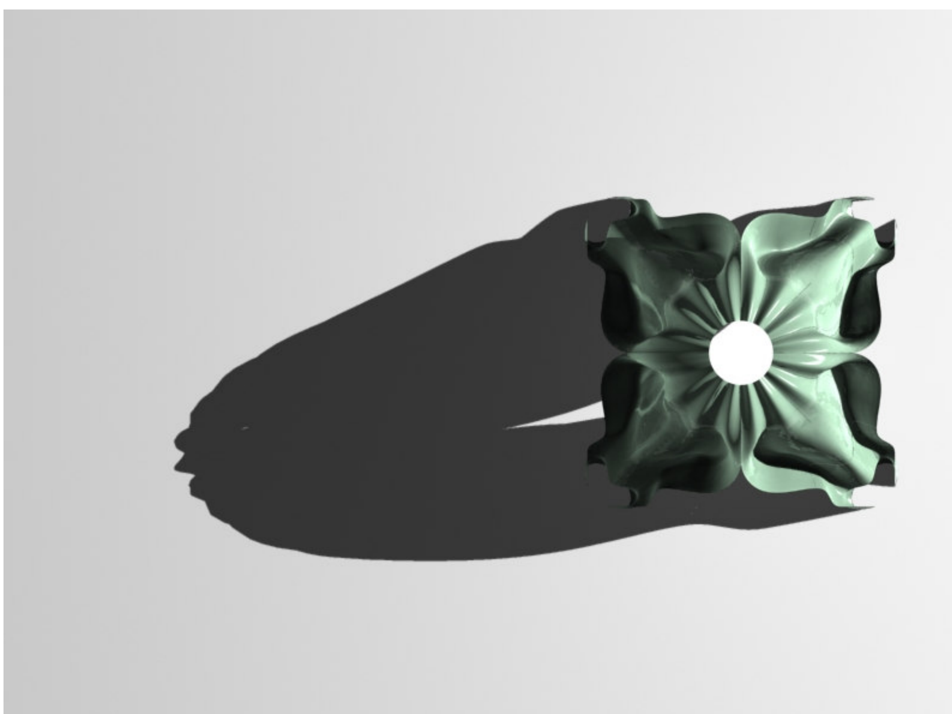


Figure 77 | Plan of first iteration dome transformation

Figure 78 | Perspective of first iteration dome transformation

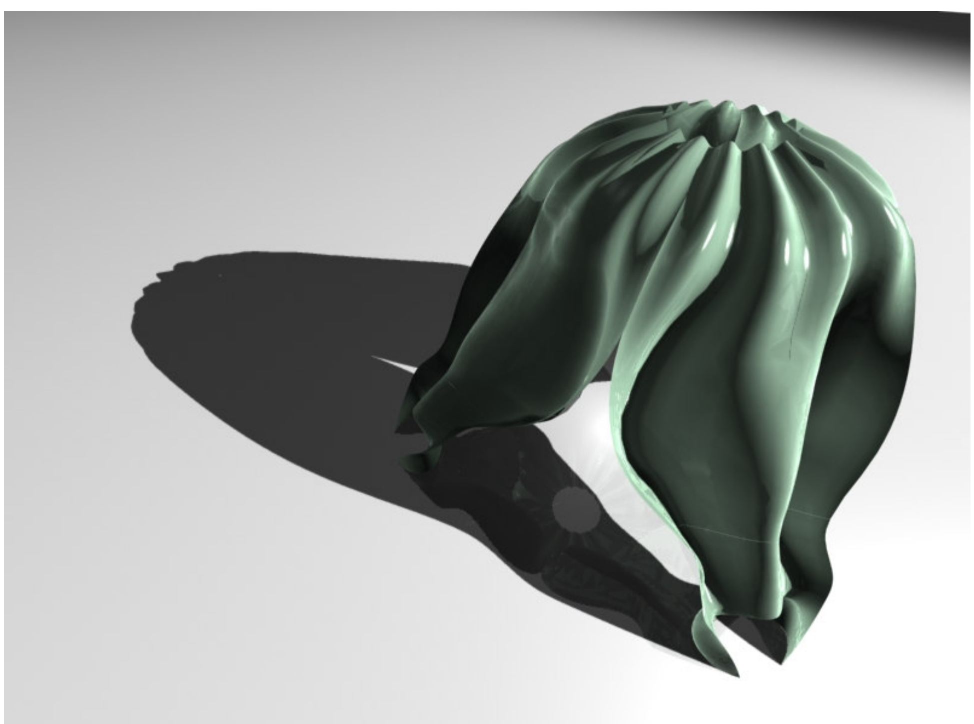


Figure 79 | Birdseye view of first iteration dome transformation

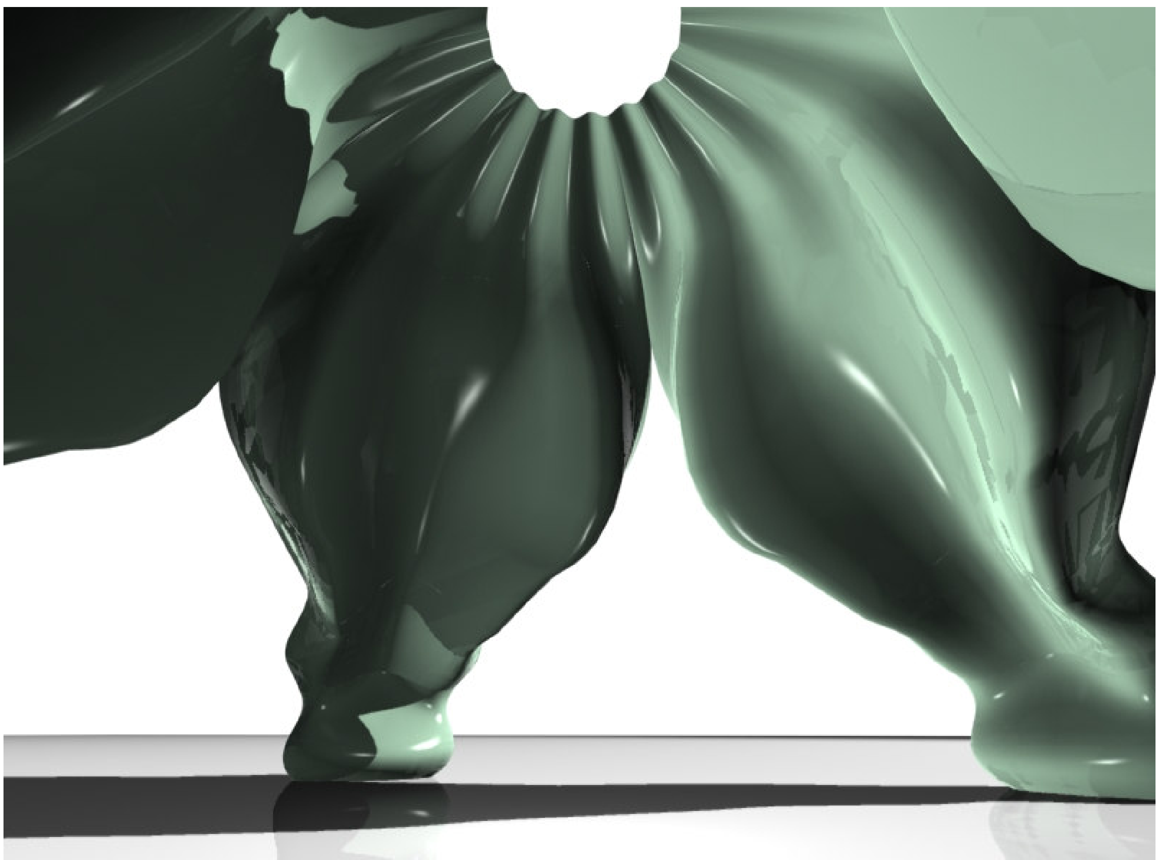


Figure 80 | Interior view of first iteration dome transformation

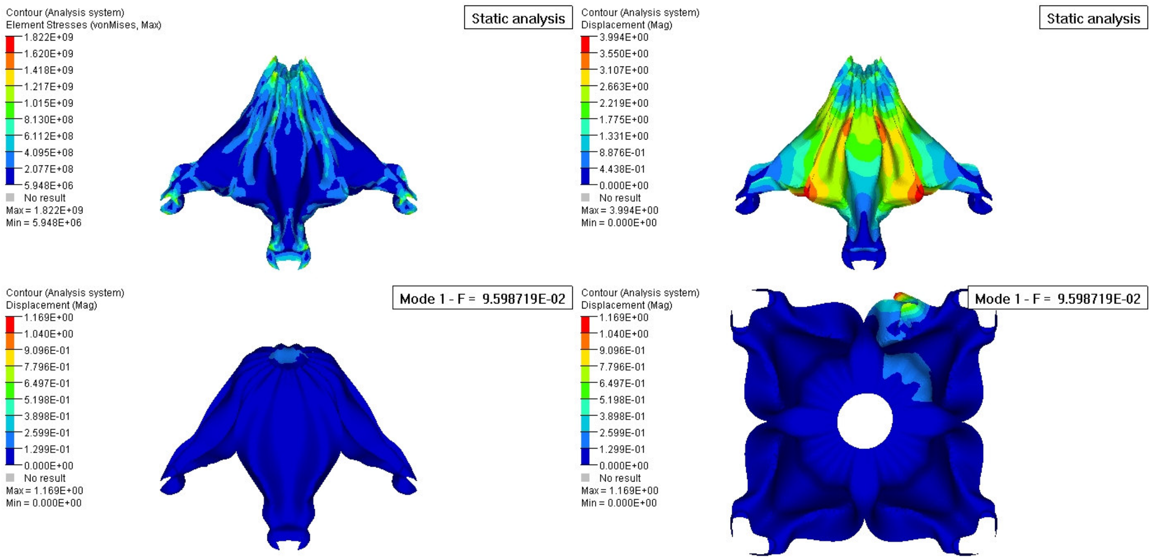


Figure 81 | Analytical results of first iteration dome transformation

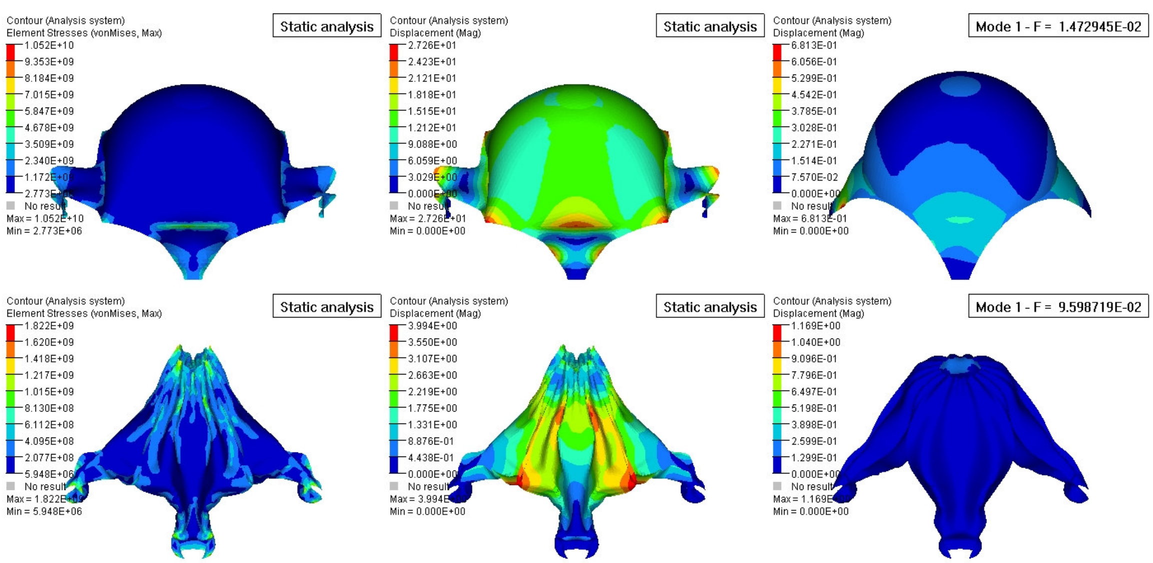


Figure 82 | Comparison of analysis between original dome and first transformation

Analysis of the first transformation showed an improvement in global buckling behavior but has also identified potential for local buckling in some surfaces. The next iteration will try to improve global buckling further by connecting the lower areas of each arch and by introducing more shape in areas prone to local buckling

Figure 83 | Perspective of second iteration dome transformation

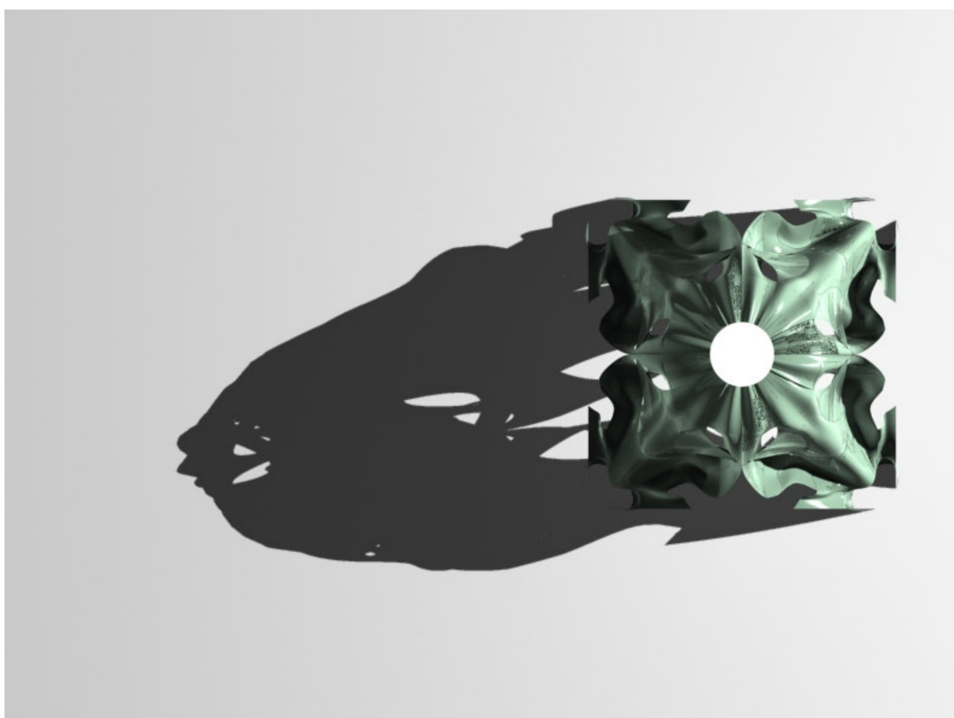


Figure 84 | Plan of second iteration dome transformation

Figure 85 | Perspective of second iteration dome transformation

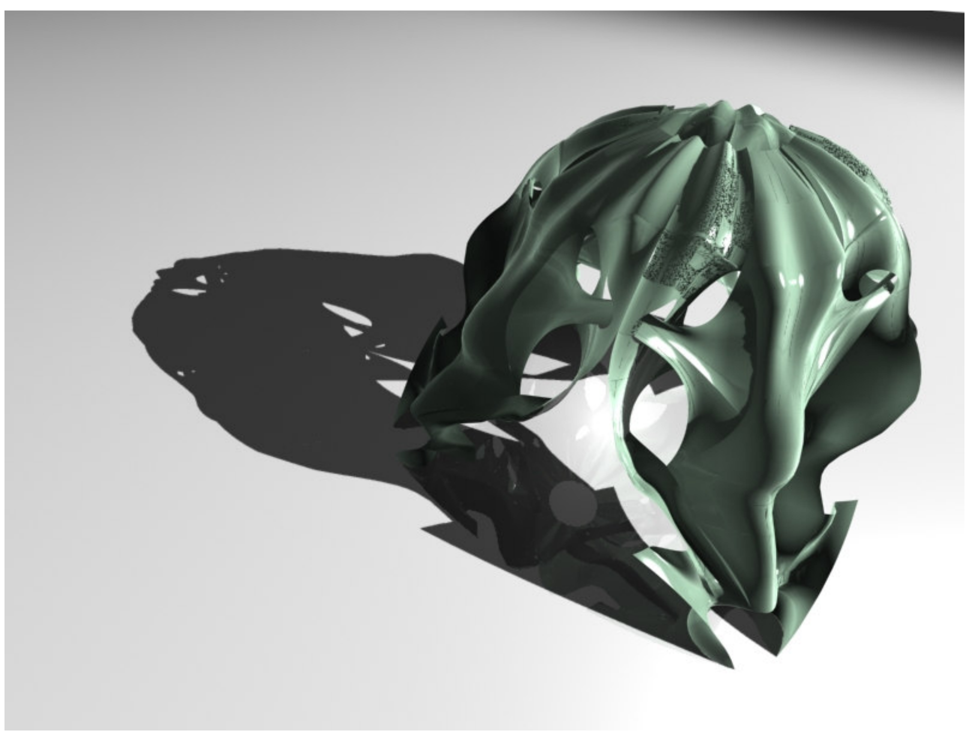


Figure 86 | Birdseye view of second iteration dome transformation

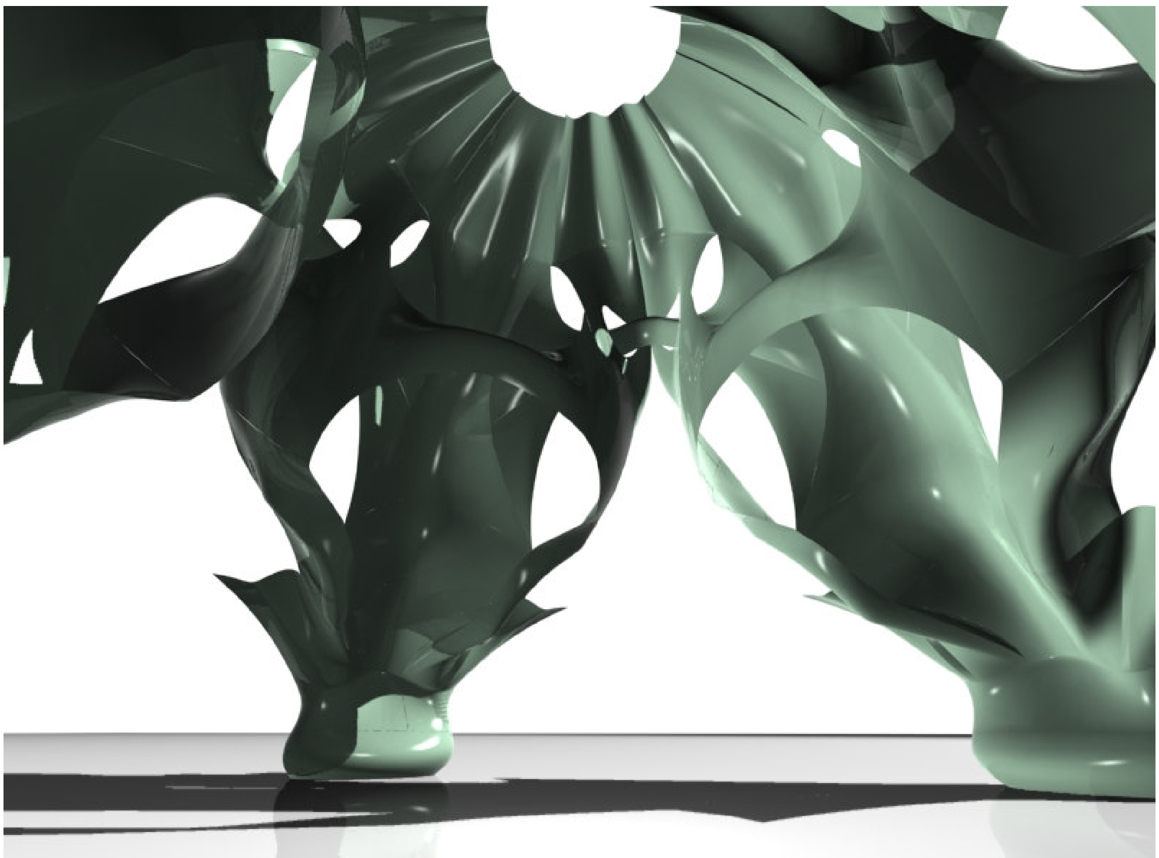


Figure 87 | Interior view of second iteration dome transformation

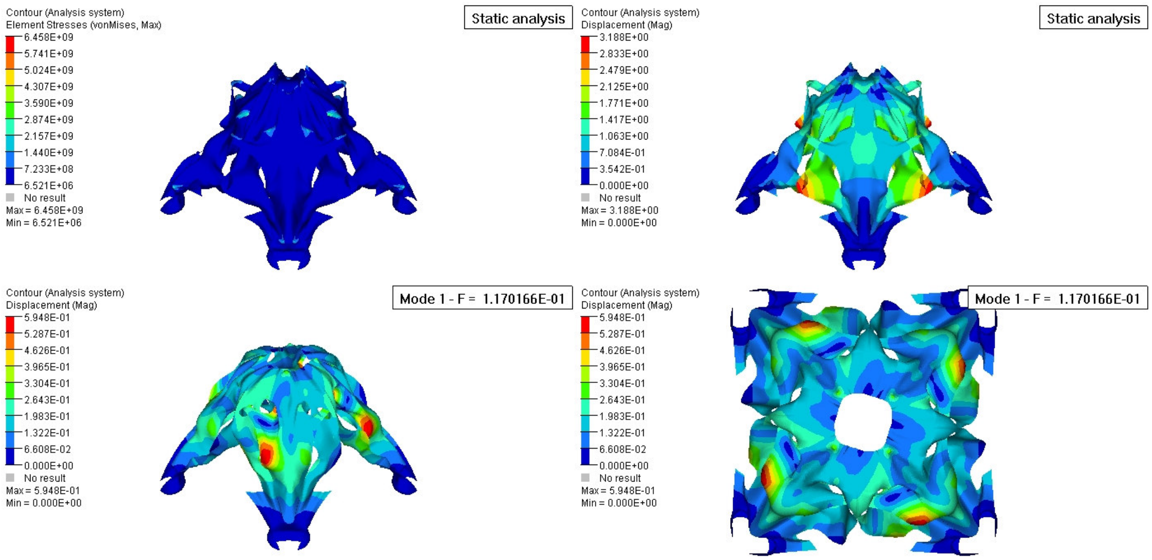


Figure 88 | Analytical results of second iteration dome transformation

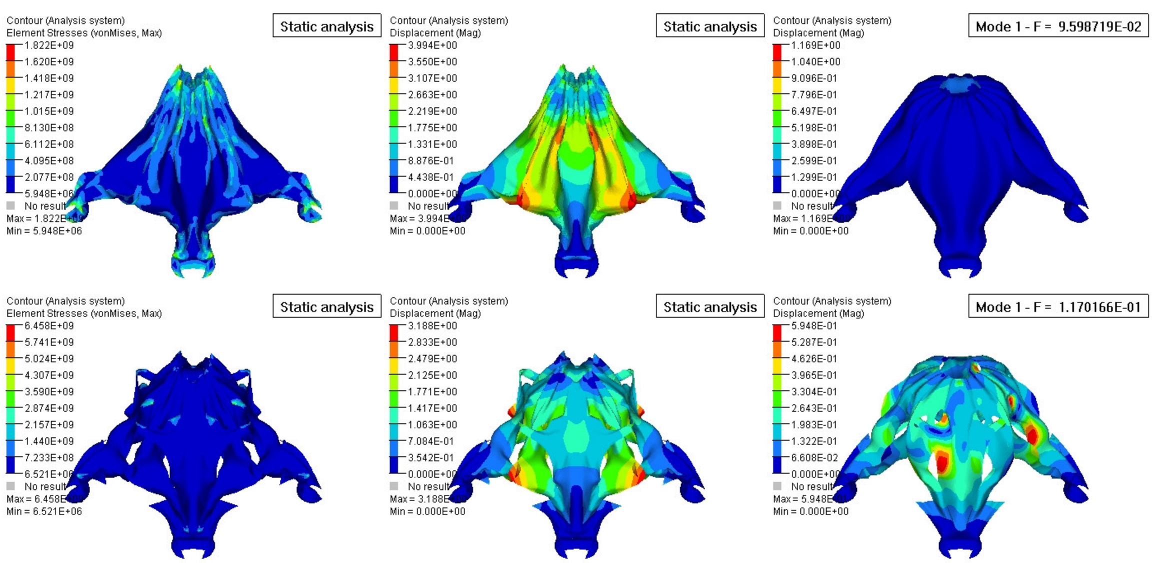


Figure 89 | Comparison of analysis between first and second transformation

Analysis of the second transformation again shows improved stiffness but the form still needs additional stiffening in the middle areas shown above as yellow and red in figure 88. The final iteration increases surface connectivity globally by making smooth toroidal transitions across previously unconnected surfaces.

Figure 90 | Perspective of third iteration dome transformation

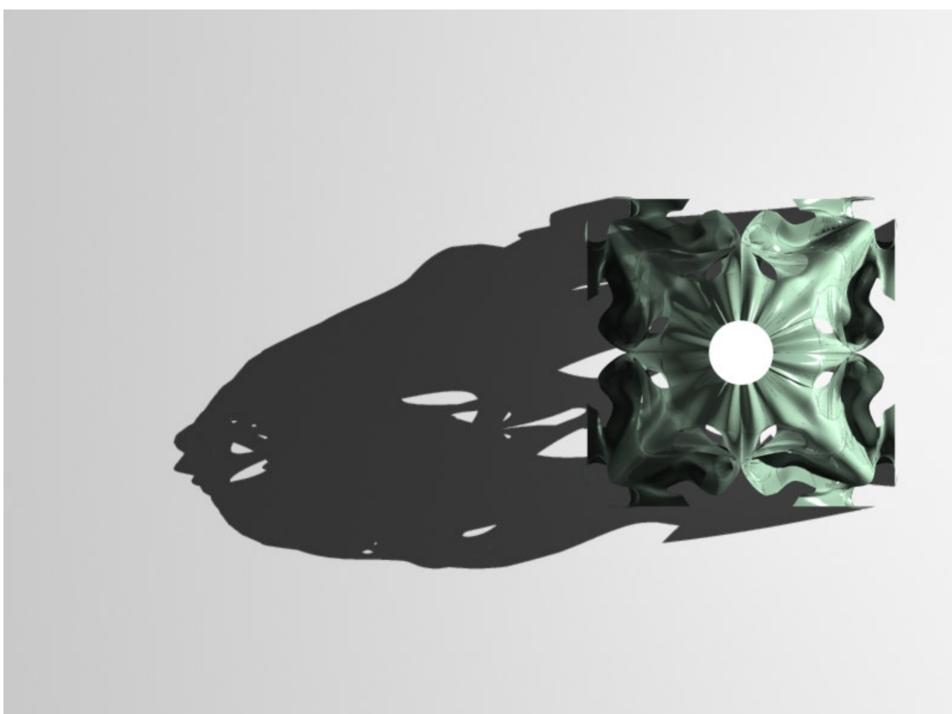


Figure 91 | Plan of third iteration dome transformation

Figure 92 | Perspective of third iteration dome transformation

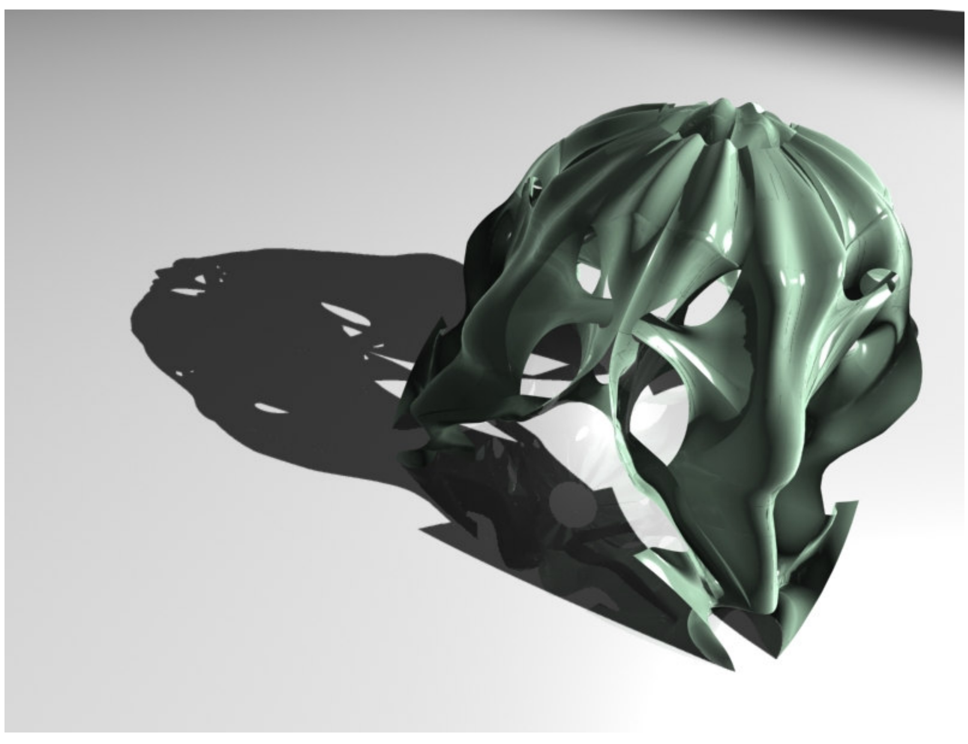


Figure 93 | Birdseye view of third iteration dome transformation

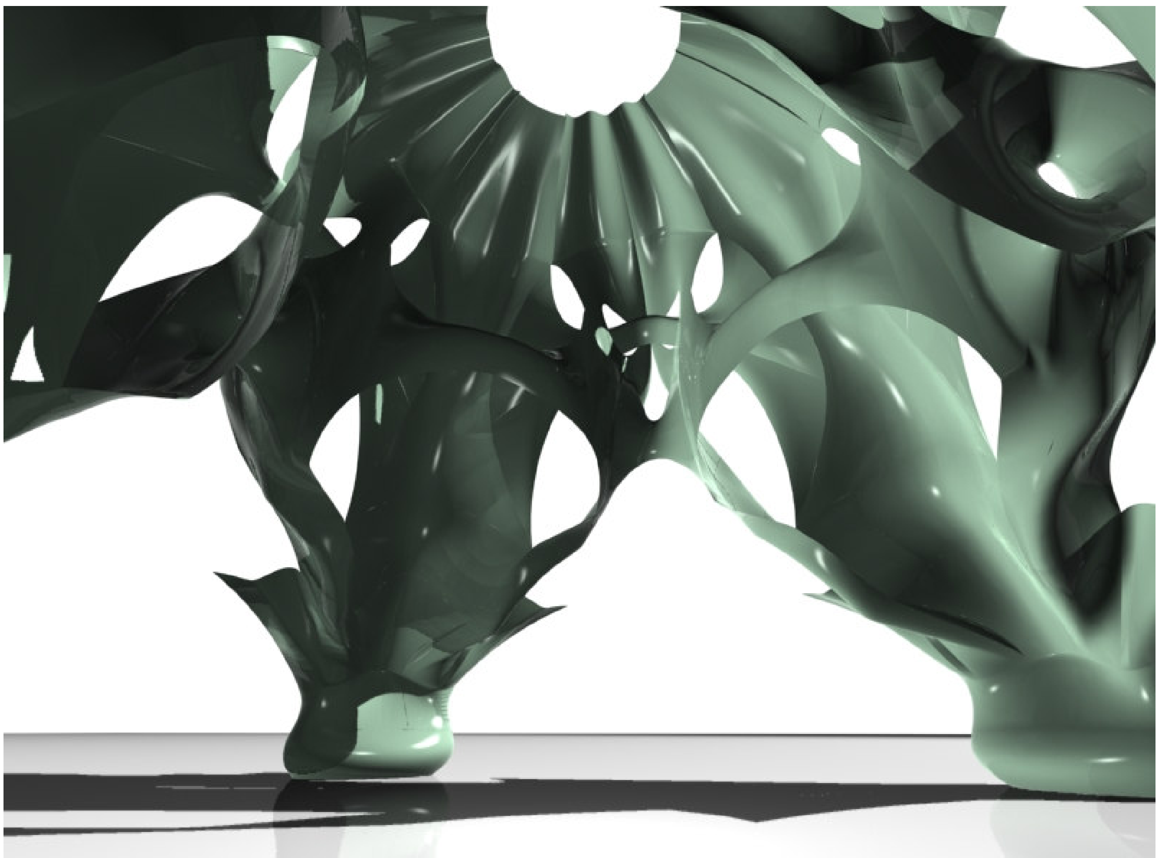


Figure 94 | Interior view of third iteration dome transformation

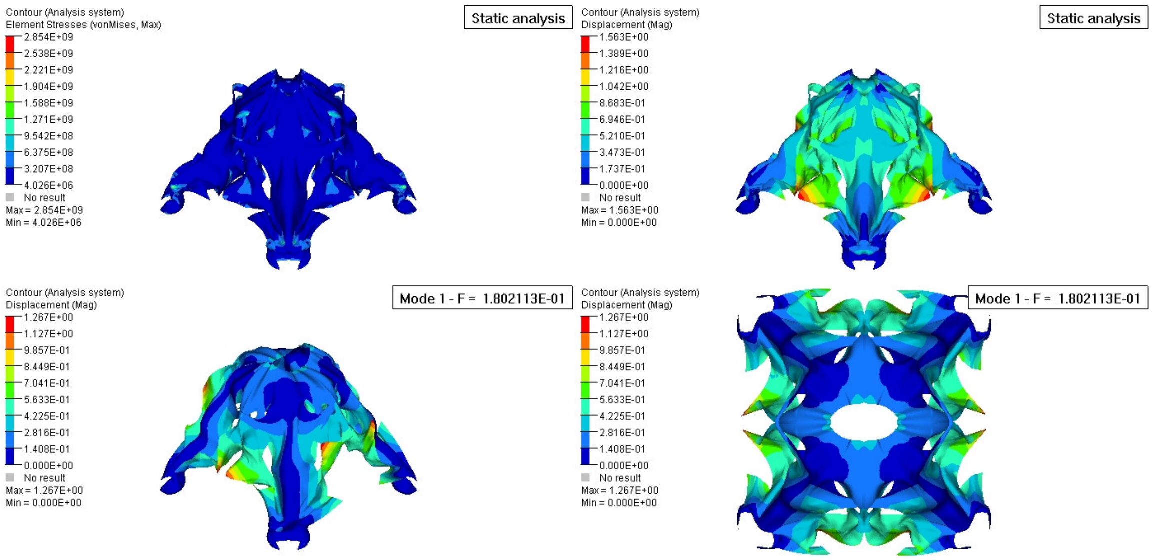


Figure 95 | Analytical results of third iteration dome transformation

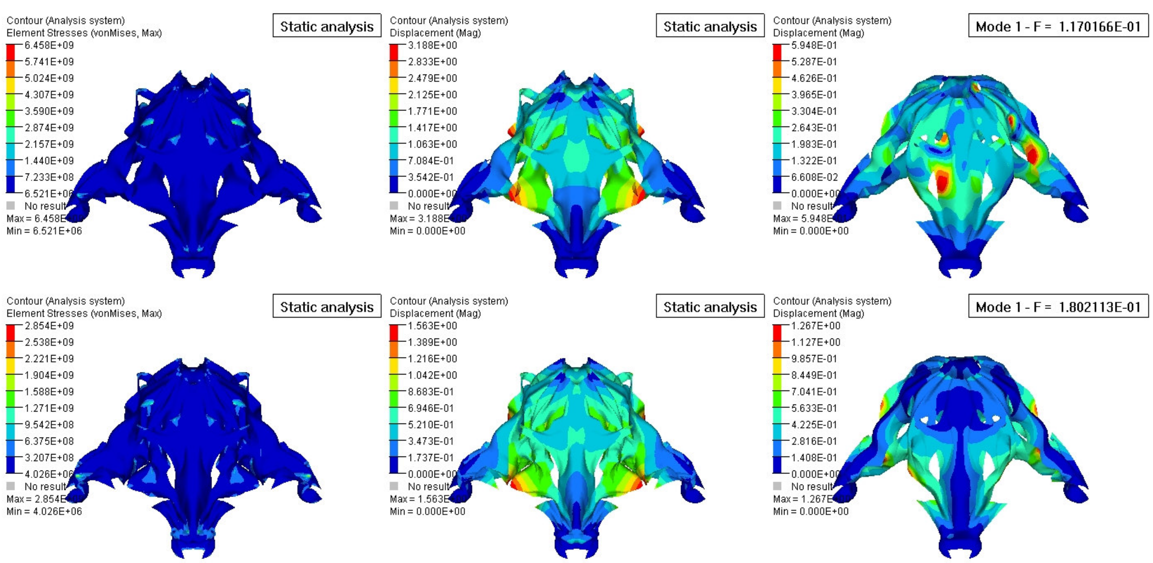


Figure 96 | Comparison of analysis between second and third transformation

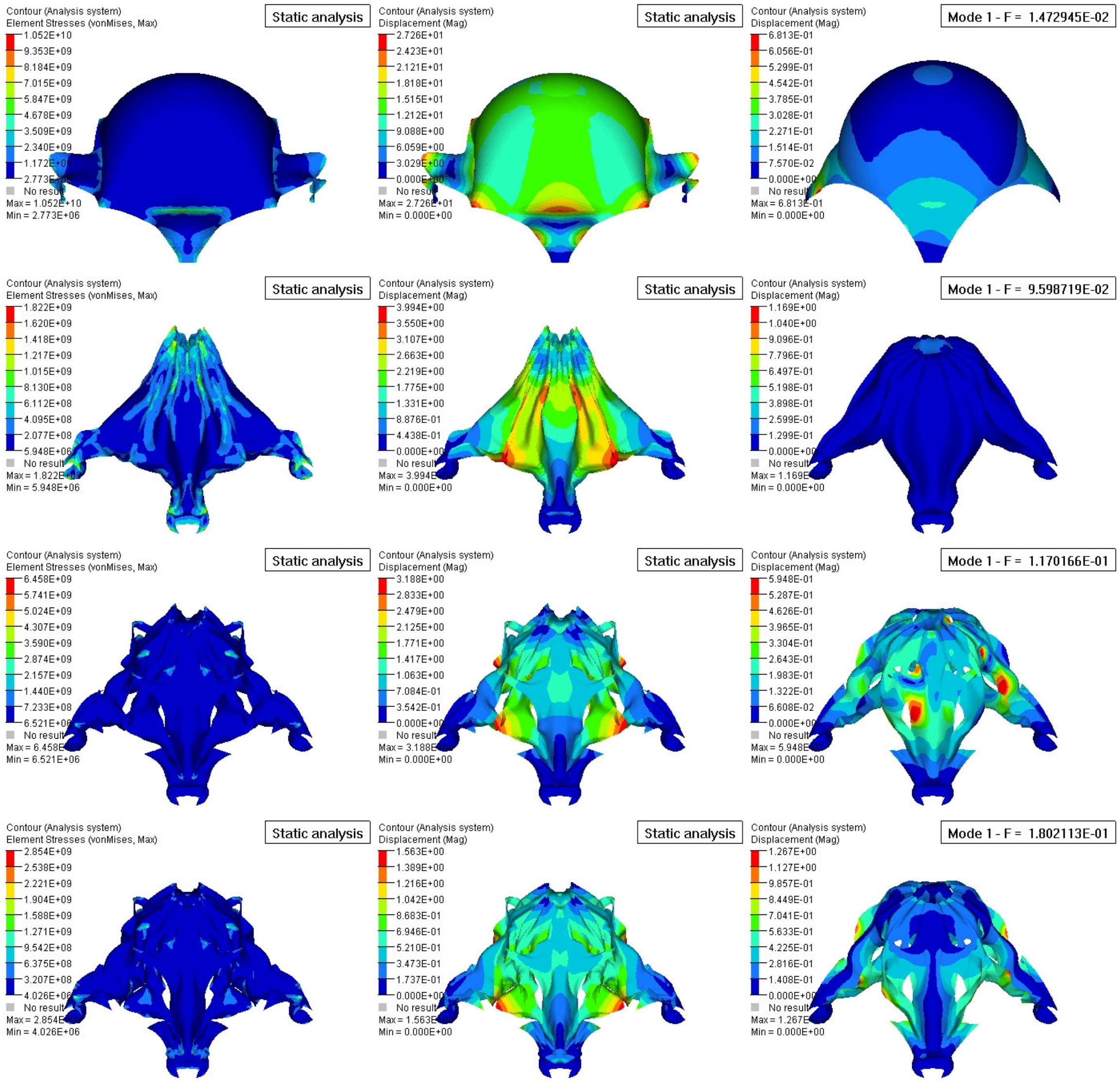


Figure 97 | Comparison of the analytical results for all shapes

Ultimately, comparative analysis between all four geometries above shows that with each set of shape stiffening operations the structural performance increases significantly. The BLF [Buckling Load Factor] is the factor by which the applied load should be multiplied in order to predict the actual load at which buckling will begin. The BLF has increased from 0.015 for the dome to 0.18 for the final iteration. The BLF for the second and third iterations is 0.096 and 0.117 respectively. This marks a twelve-fold increase in stiffness from the original geometry to the final geometry. Maximum displacements have also been significantly reduced from 27.3 units to 1.6 units, marking a 17-fold decrease in maximum displacements.

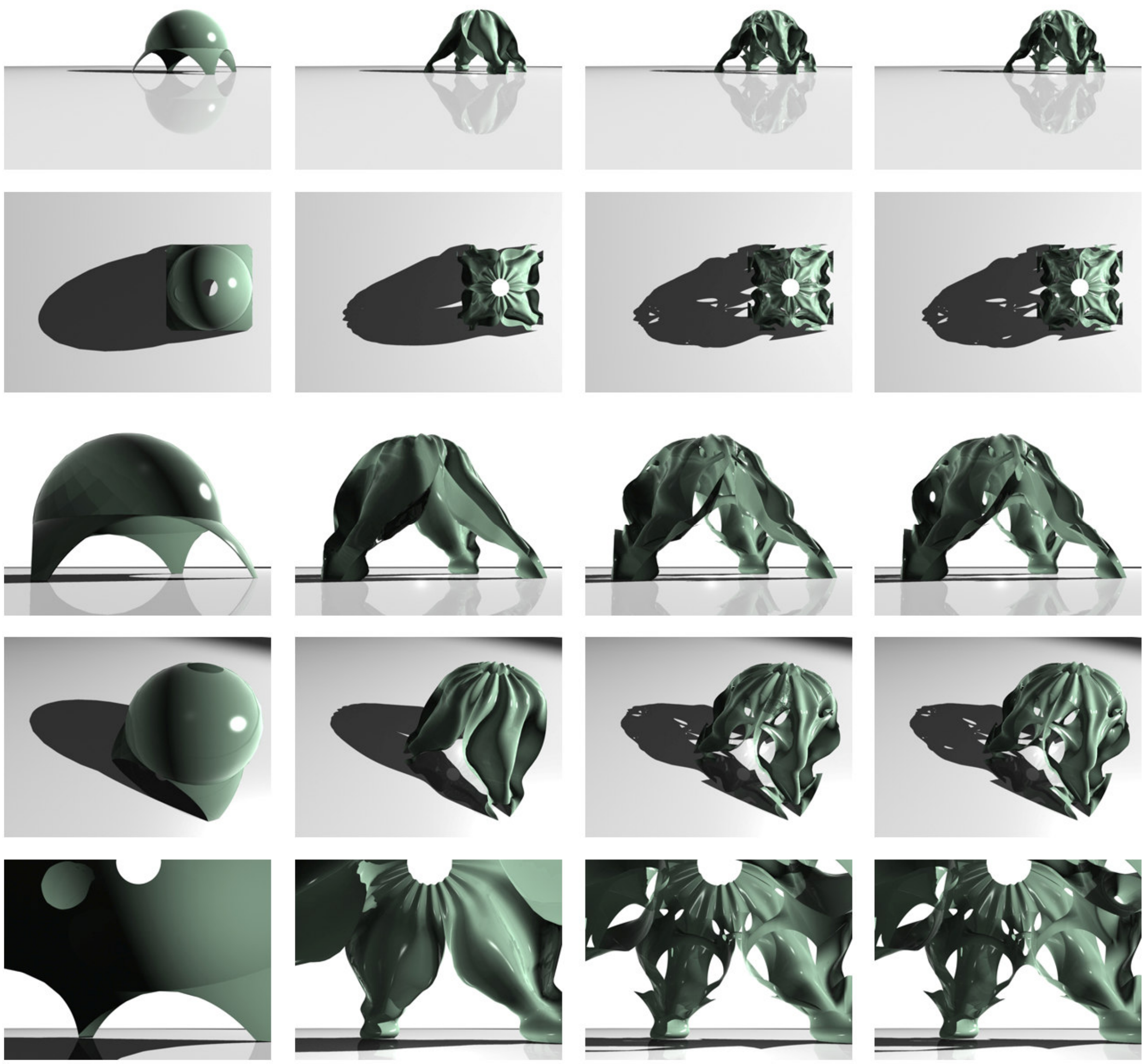


Figure 98 | Progression of geometric transformation

CHAPTER 11 | CONCLUSIONS

The process presented here has been successful as an analytical guide for designers wanting to use material behavior and shape stiffness as primary drivers for designing and building complex surface geometries. FEA is a clear verification of the premise that 3D *shape* increases stiffness. Through this process geometric complexity can also be significantly increased and it could be argued that these techniques have produced an intricately articulated surface, or contemporary structural ornamentation. Formal aesthetics, design intensions/intuitions, geometry, material, and physical behavior have all converged in this process to produce a rich form where structure and skin, concept and construct, and process and product can be understood simultaneously through a continuum of surface.

Excluding the time necessary for geometric modeling, each of these FE analyses took approximately 30 minutes to setup, solve, and format the results. This is a powerful demonstration of how this method could very feasibly be incorporated into a daily design cycle. One workday could easily produce 3-4 geometric possibilities, depending on geometric complexity, with relatively accurate behavioral models demonstrating structural feasibility and potentials for further geometric development. Additionally, as true parametric modeling is quickly becoming normalized in design offices one could easily imagine producing 10-20 geometric and analytical daily derivations for a project.

The deployment of this technology and these techniques as presented above is immediate. FEA is over 50 years old now and has already found its way into the background of many CAD packages used on desktop machines in architectural offices. Only desire is needed to implement this technique. The potential for future research lies in using FEA to design with non-linear, dynamic behaviors in mind. This method shows tremendous promise for developing even richer structures that are intentionally designed to accommodate, and even promote large-scale movement. Applications for such structures include seismic design, hurricane design, blast resistance design, deployable structures, responsive environments, art installations, et cetera. This research has only scraped the surface of what is possible for the future of design and engineering.

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